Using CERES to understand the atmospheric energy budget and tropical rainfall variations

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Berkeley
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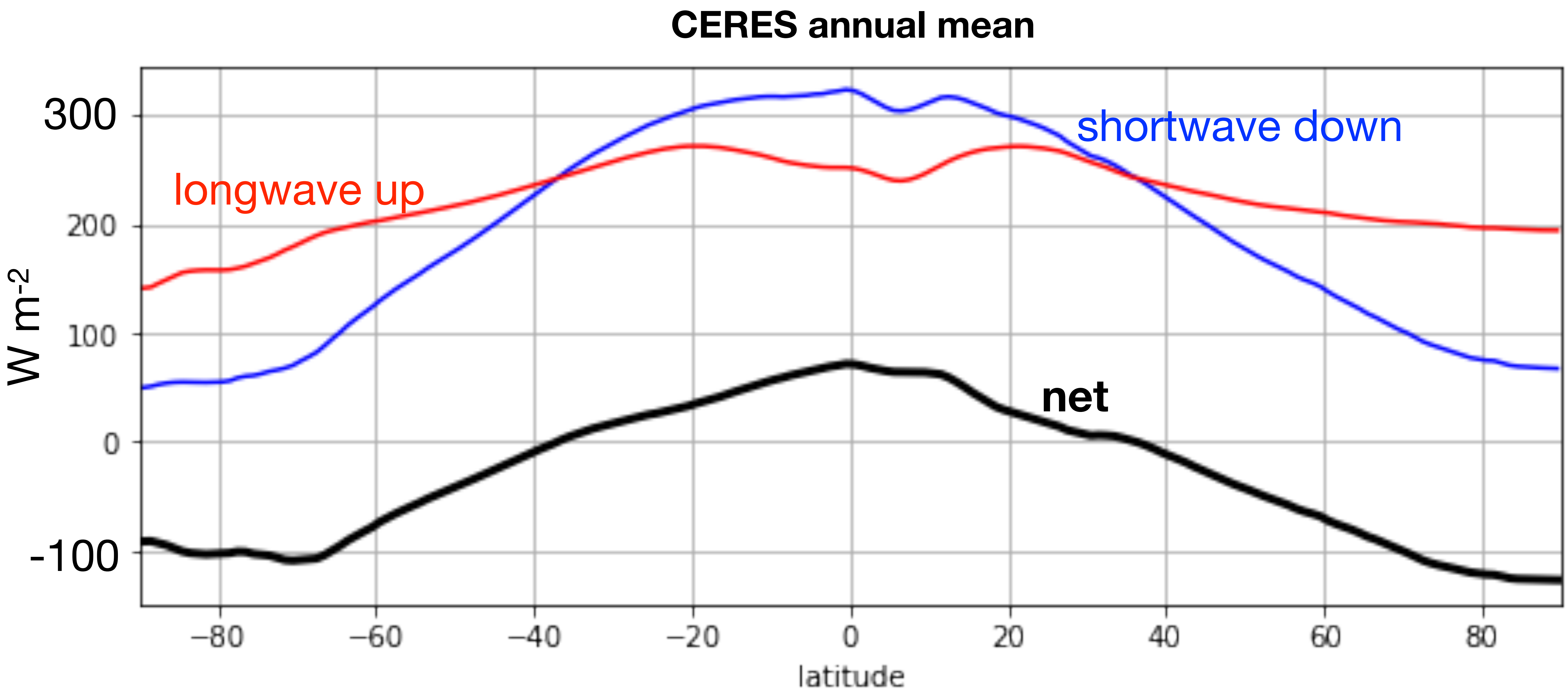
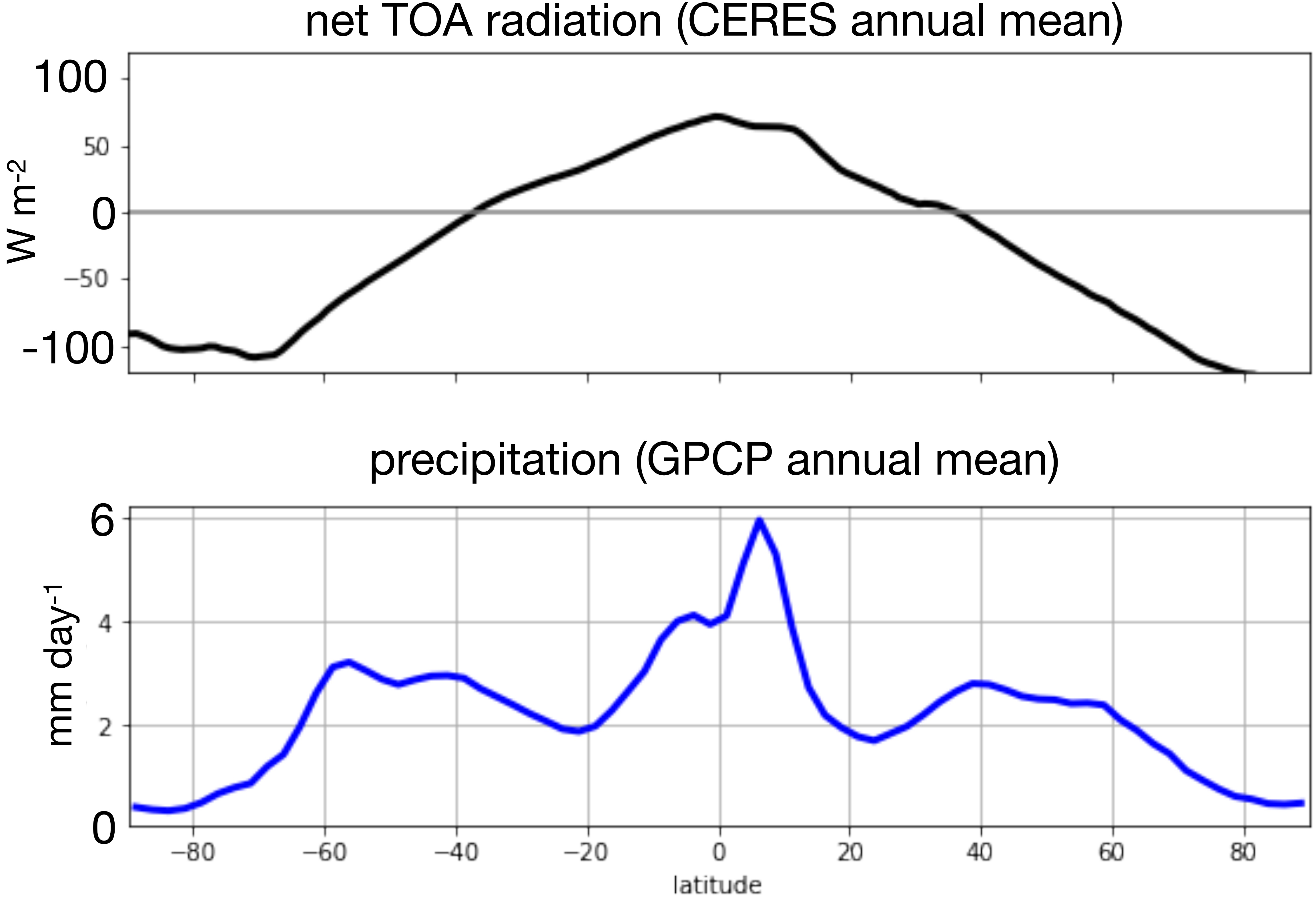
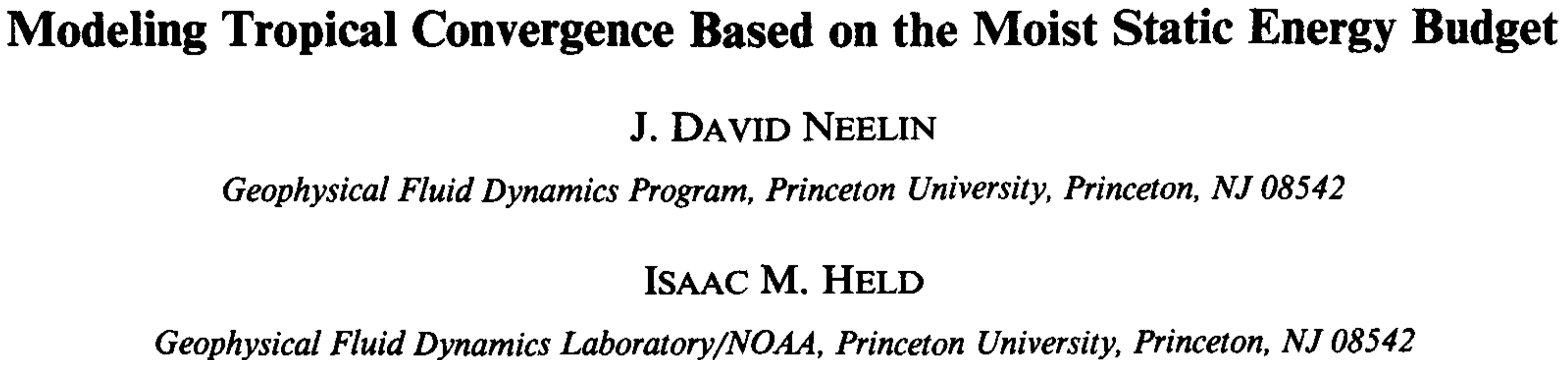
Earth's top-of-atmosphere radiative imbalance



This net radiative input drives the global atmospheric circulation, which in turn sets the distribution of precipitation



Can we infer the circulation & rainfall directly from the net radiation?



Modeling Tropical Convergence Based on the Moist Static Energy Budget

J. DAVID NEELIN

Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ 08542

ISAAC M. HELD

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Can we infer the circulation & rainfall directly from the net radiation?

$$h = c_p T + gz + L_v q$$

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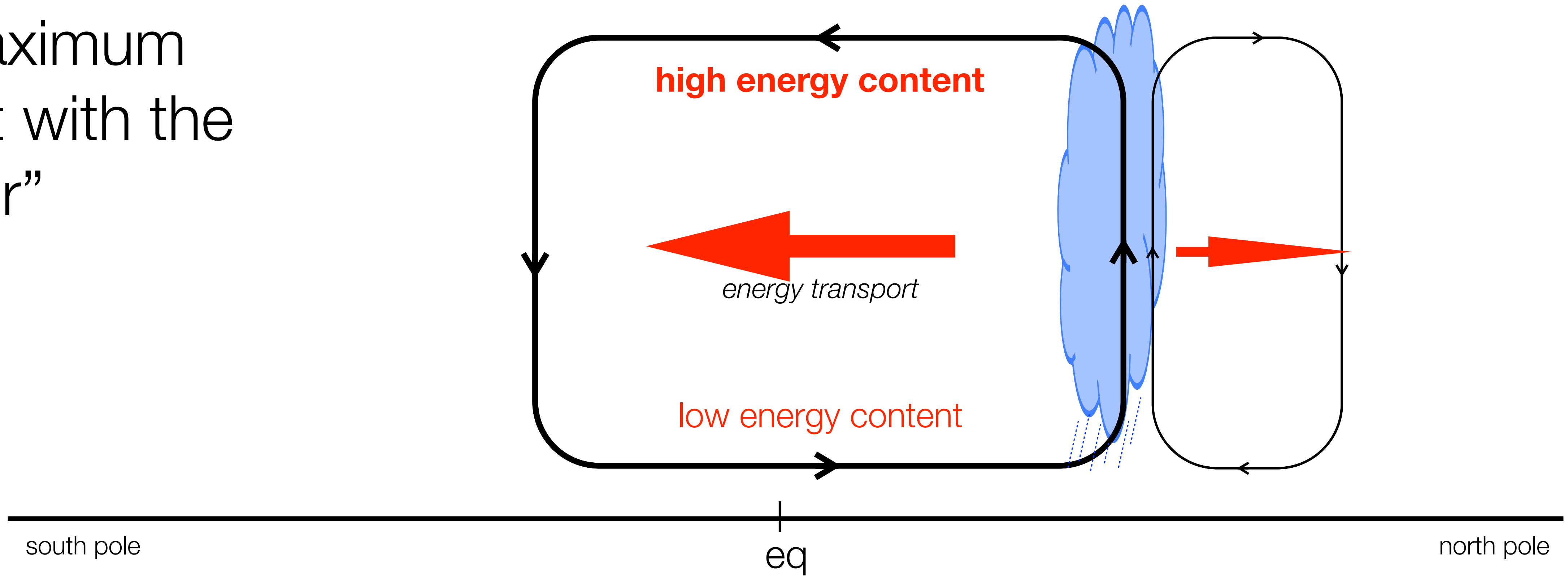
moist energy budget:

$$\partial_t h + \mathbf{u} \cdot \nabla h + \omega \partial_p h = F_{net}$$

vertically integrate, time average, neglect horizontal gradients:

$$-\hat{\omega} \left\langle -\Omega \partial_p h \right\rangle = \left\langle F_{\text{net}} \right\rangle$$

Progress in last decade: instead assume maximum rainfall is coincident with the "energy flux equator"



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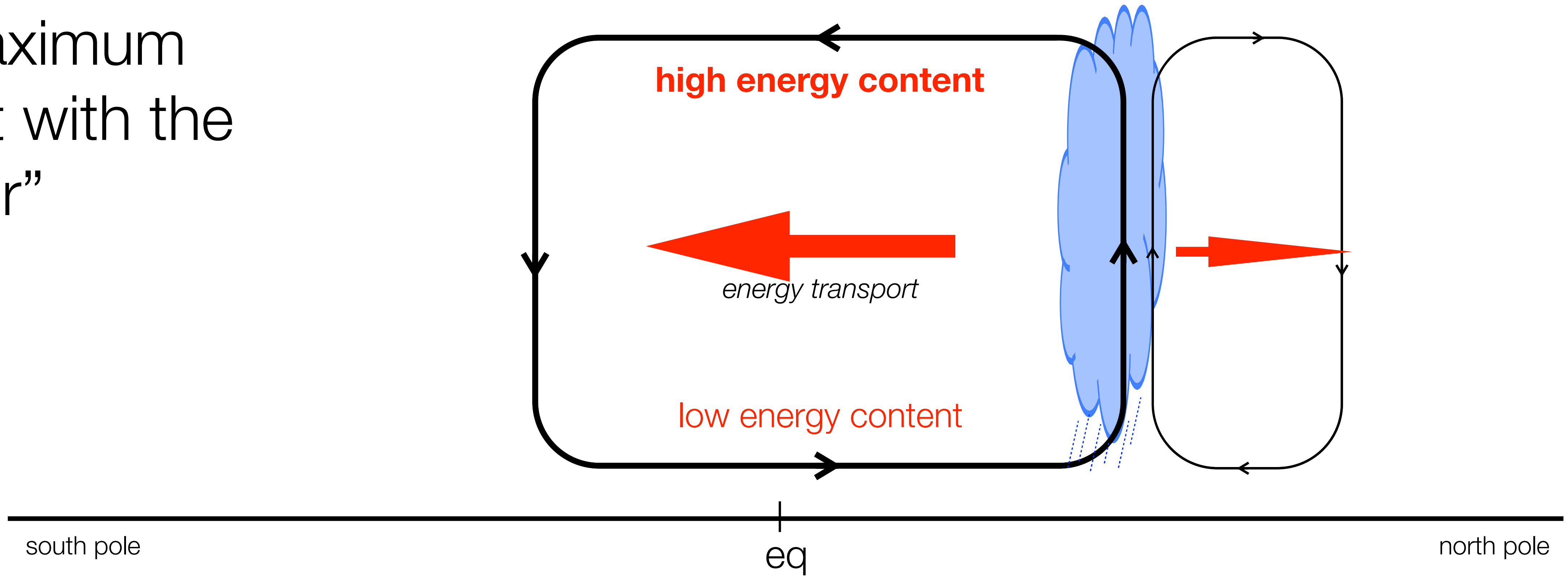

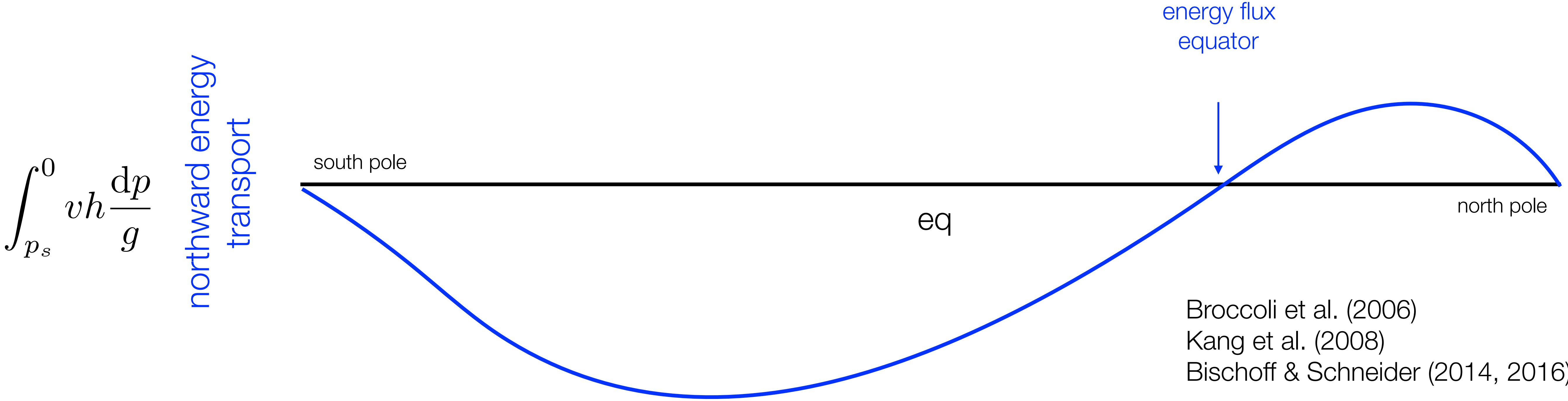

Broccoli et al. (2006)
Kang et al. (2008)
Bischoff & Schneider (2014, 2016)

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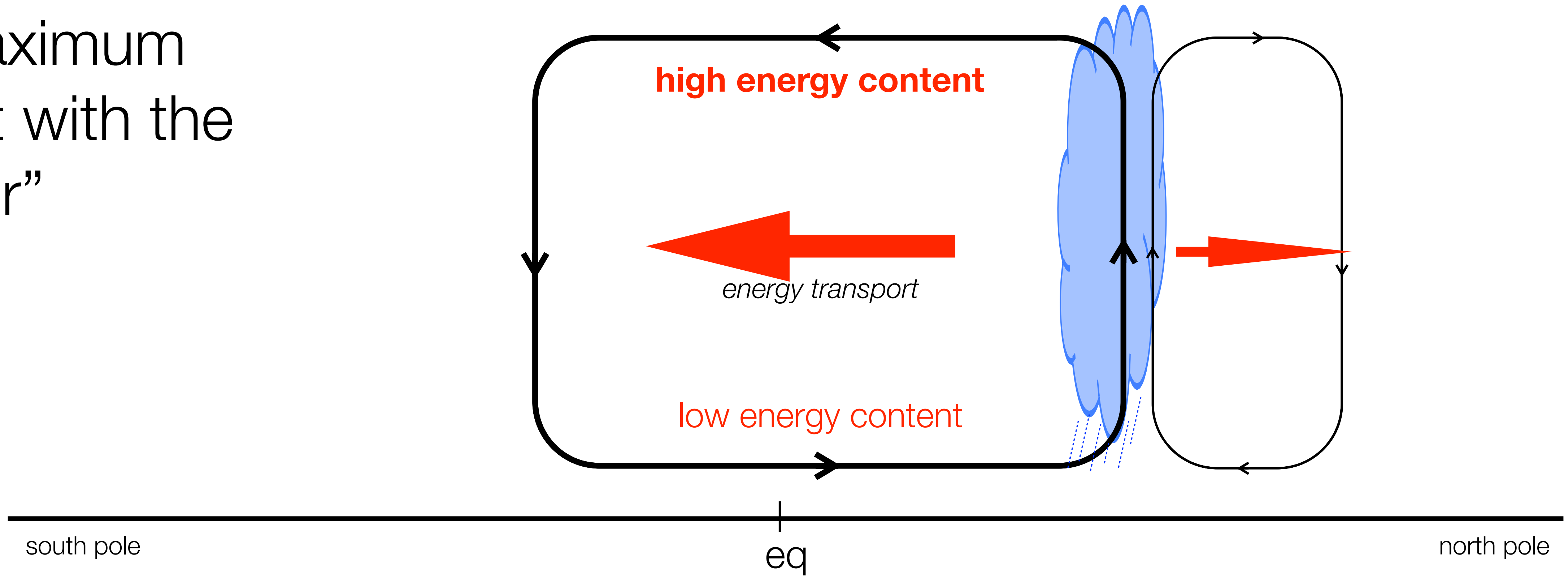
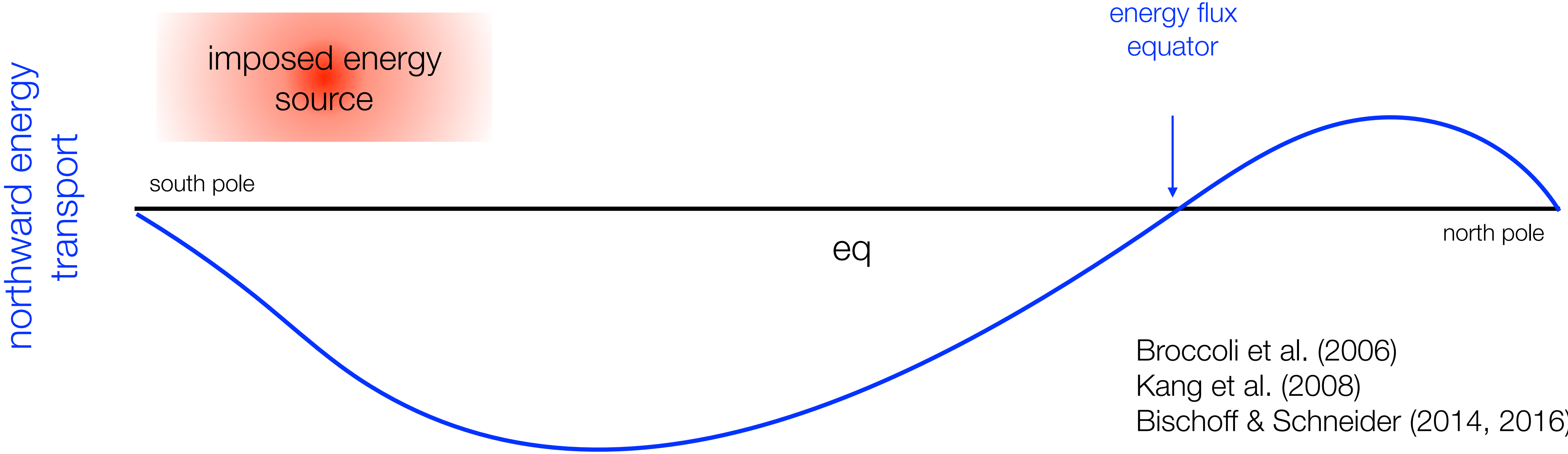


$$\int_{p_s}^{0} vh \frac{\mathrm{d}p}{g}$$



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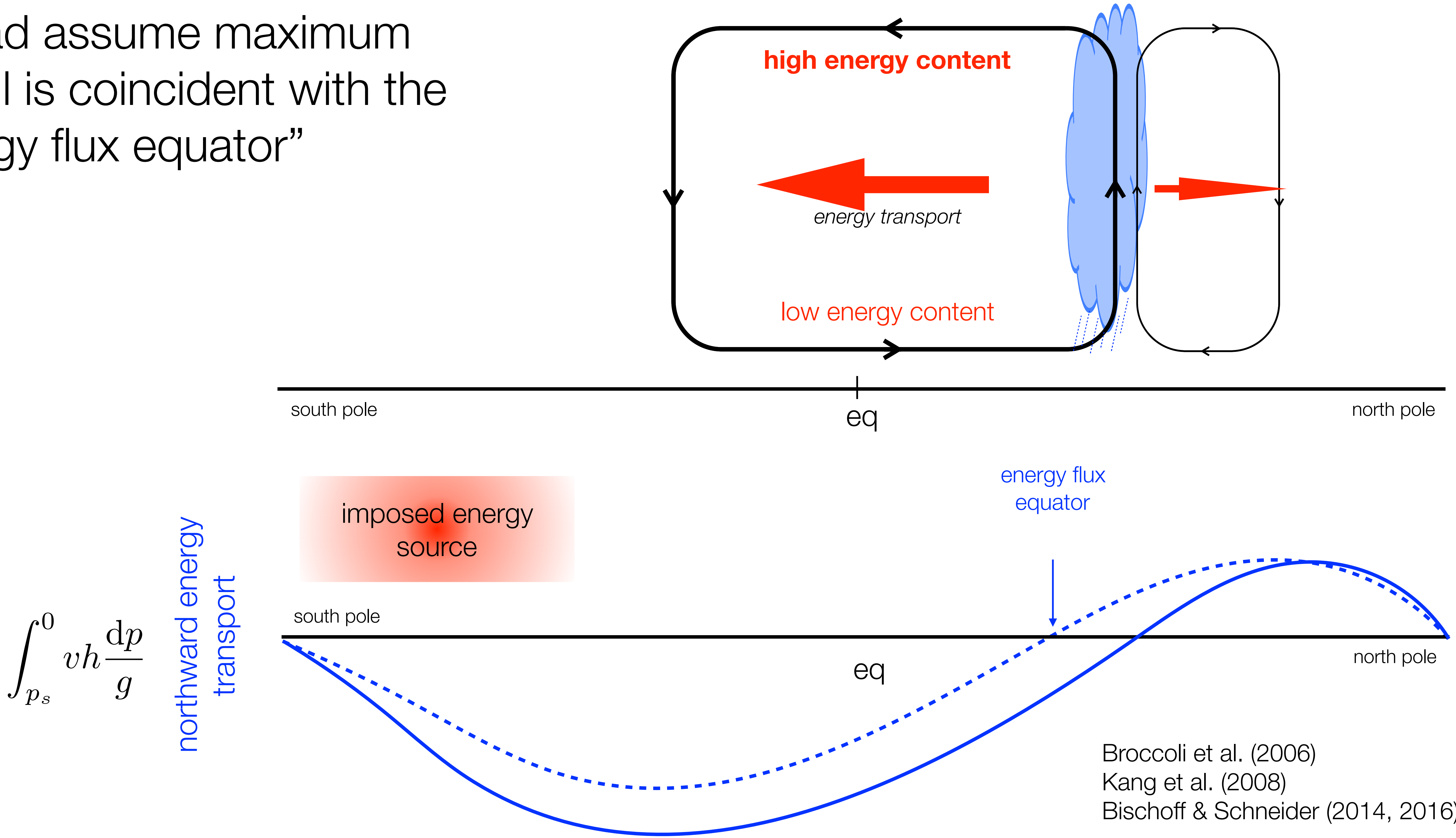

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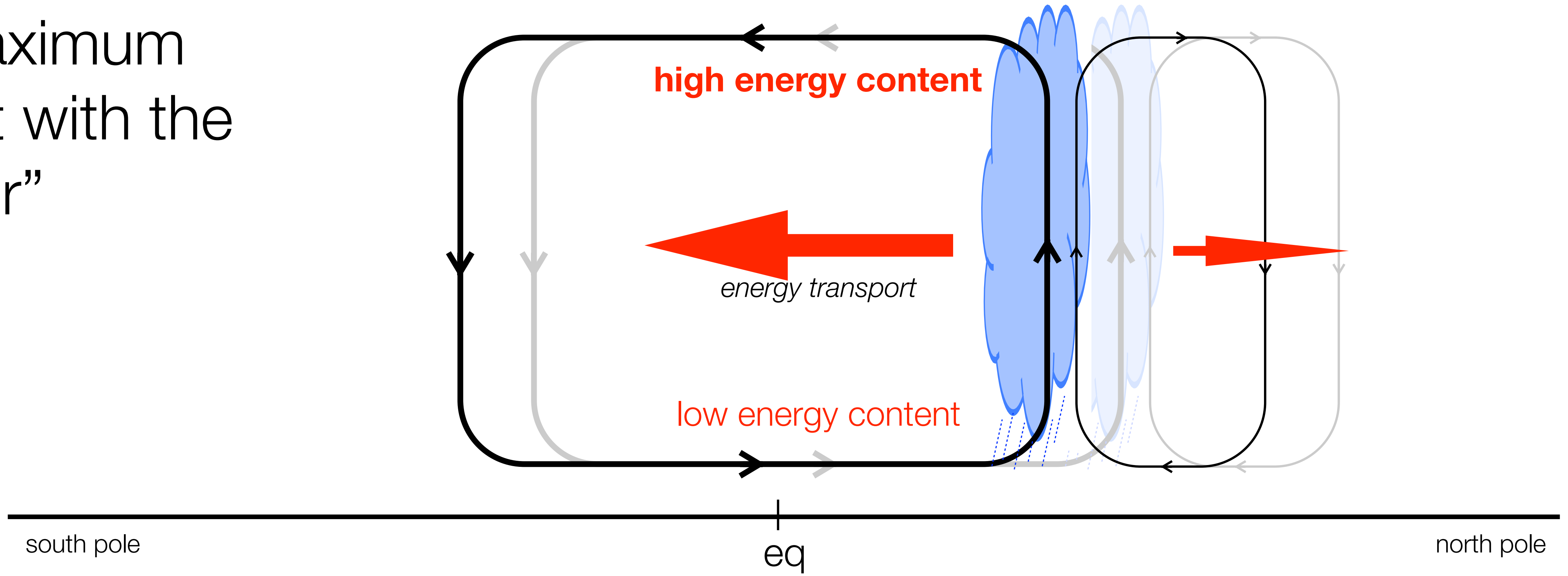
3º latitude ITCZ shift per PW of cross-equatorial energy transport



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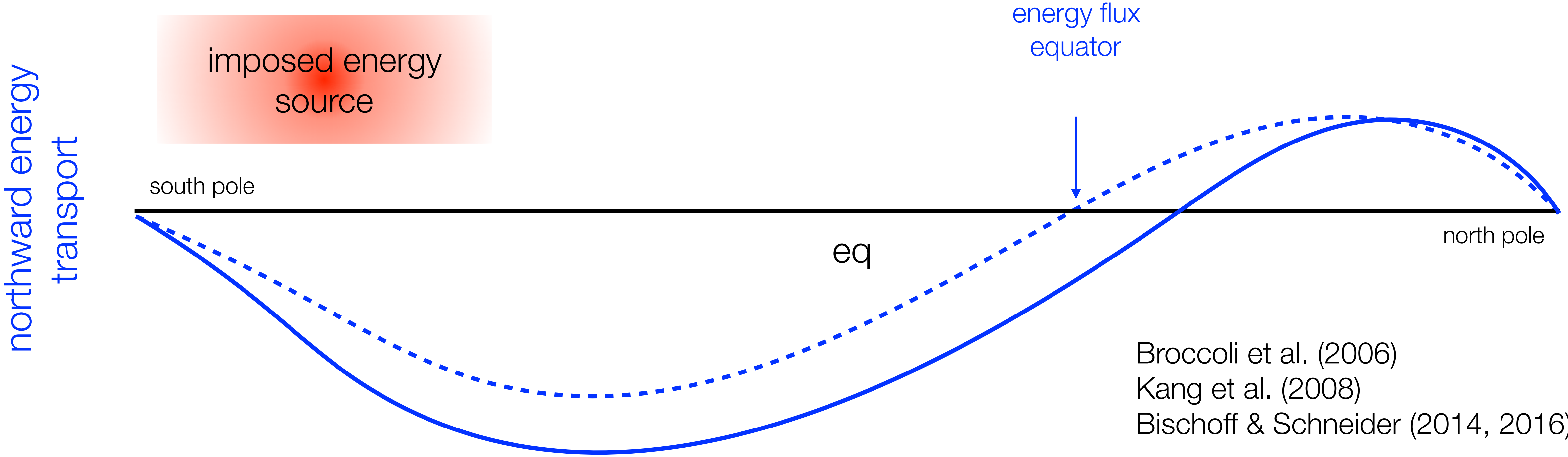

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Let's go beyond the zonal mean, by combining CERES radiative fluxes with estimates of surface turbulent fluxes

atmospheric vertically integrated moist energy budget:

$$\partial_t \langle h \rangle + \nabla \cdot \langle \vec{u} h \rangle = R_{\mathrm{surf}} - R_{\mathrm{TOA}} + E + H$$

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CERES

OAFlux (WHOI)

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ocean:

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land:

surface energy budget: $$C \partial_t T_s = R_{\mathrm{surf}} + E + H$$

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ocean:

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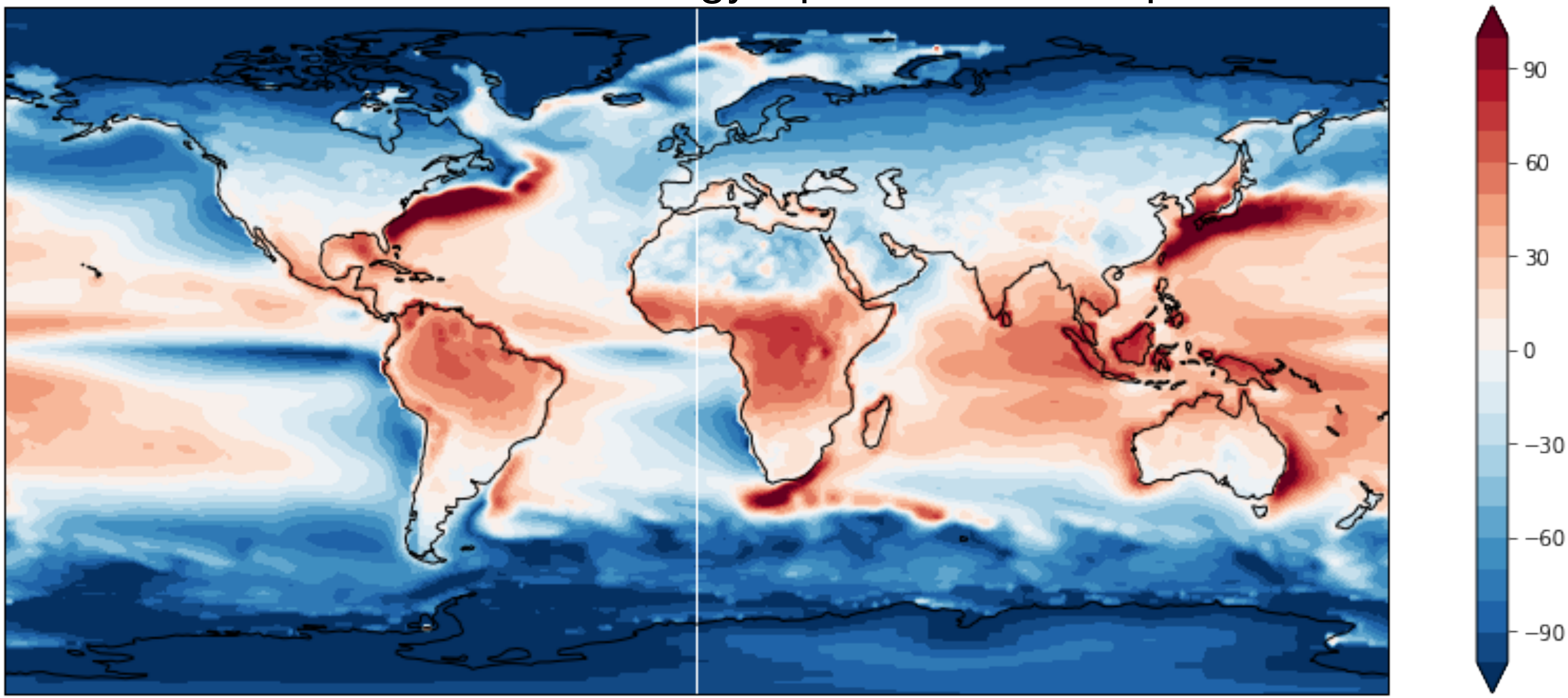
atmospheric vertically integrated moist energy budget:

$$\cancel{\partial_t \langle h \rangle} + \nabla \cdot \langle \vec{u} h \rangle = -R_{\mathrm{TOA}}$$

CERES

CERES radiation + OAFlux surface turbulent fluxes

annual mean net energy input to the atmosphere



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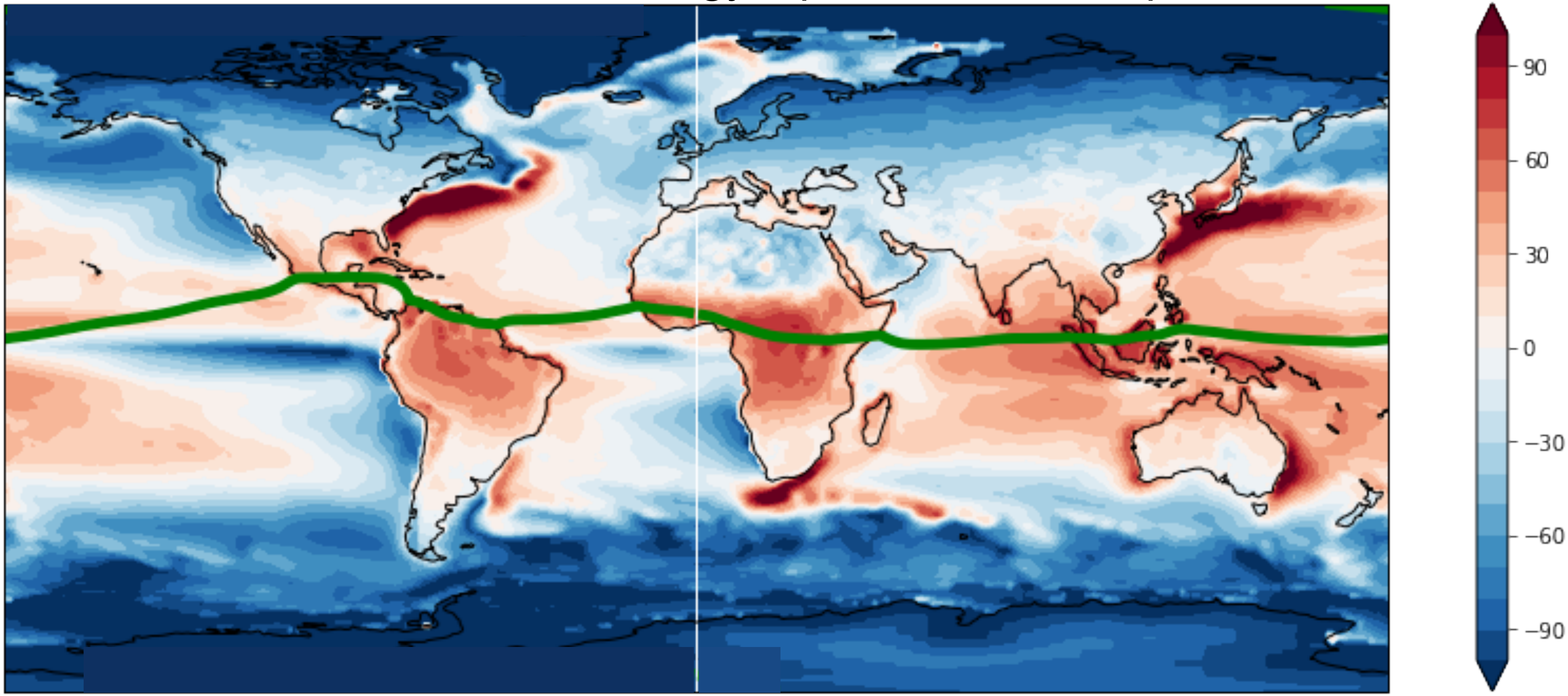

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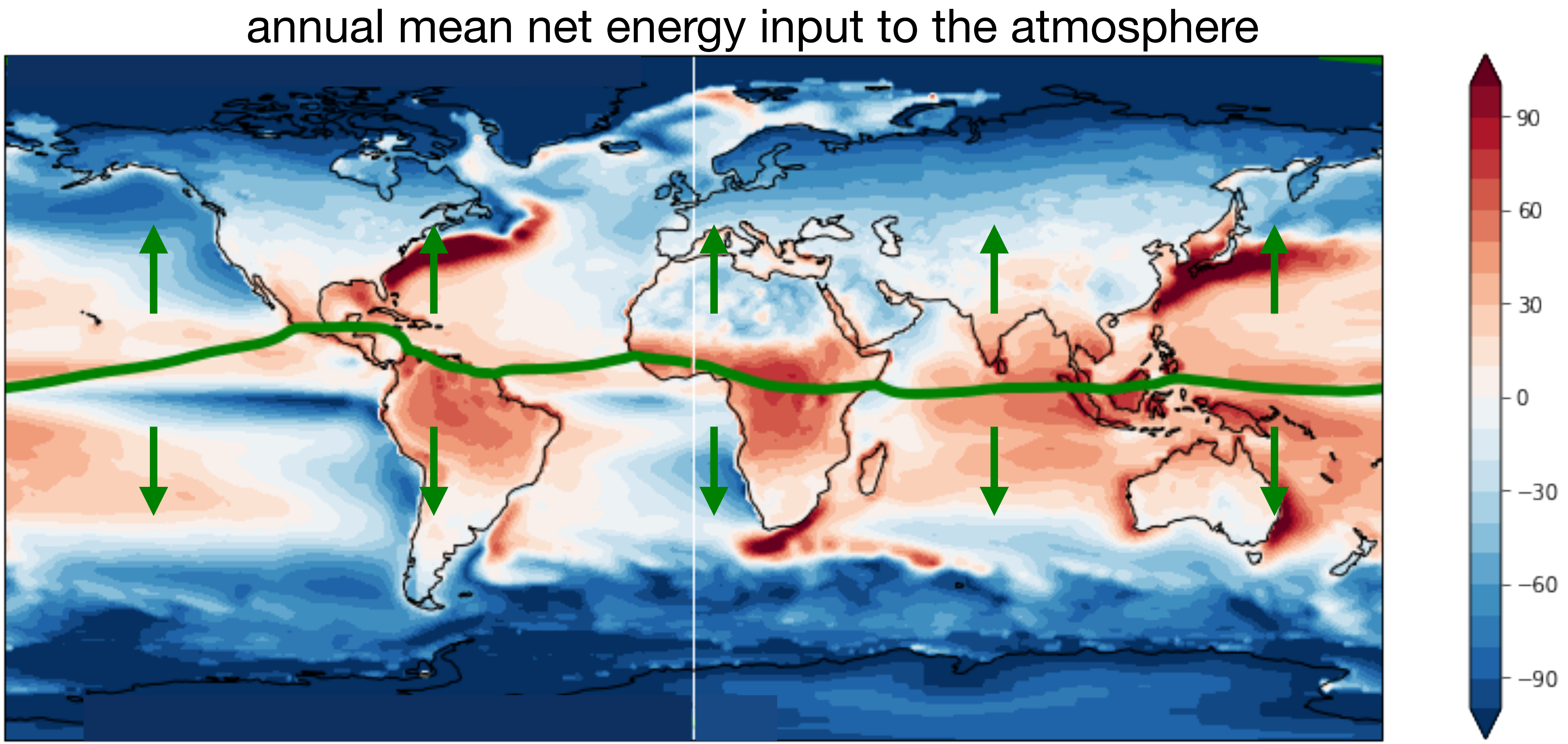


Now let's do two applications

1. Earth's seasonal cycle — some surprising effects of clouds on precipitation

2. The very persistent precipitation bias in climate models

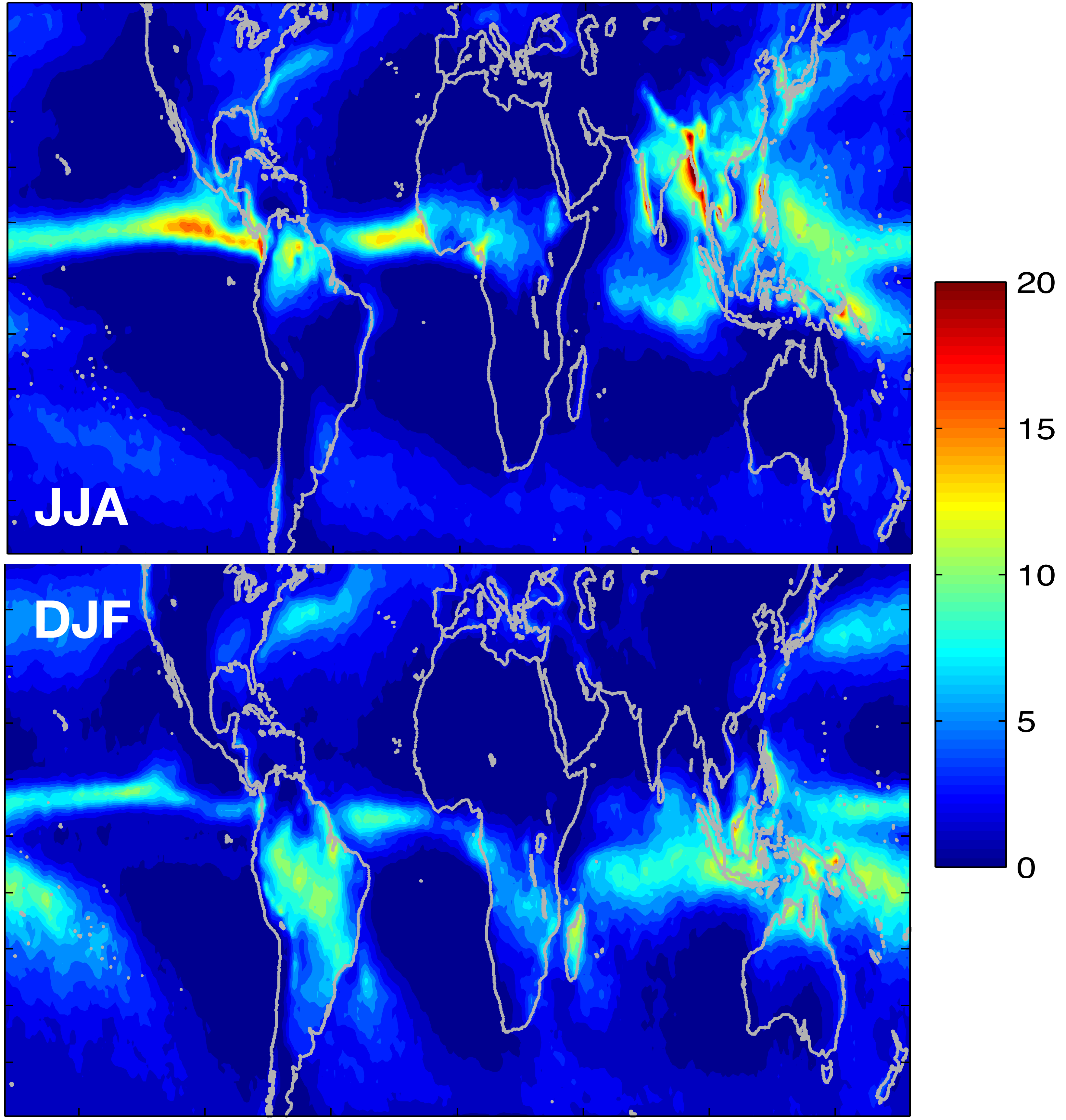
Now let's do two applications

1. **Earth's seasonal cycle — some surprising effects of clouds on precipitation**

2. The very persistent precipitation bias in climate models

Earth has a large seasonal cycle of rainfall, mostly associated with monsoons

observed seasonal mean rainfall (TRMM)



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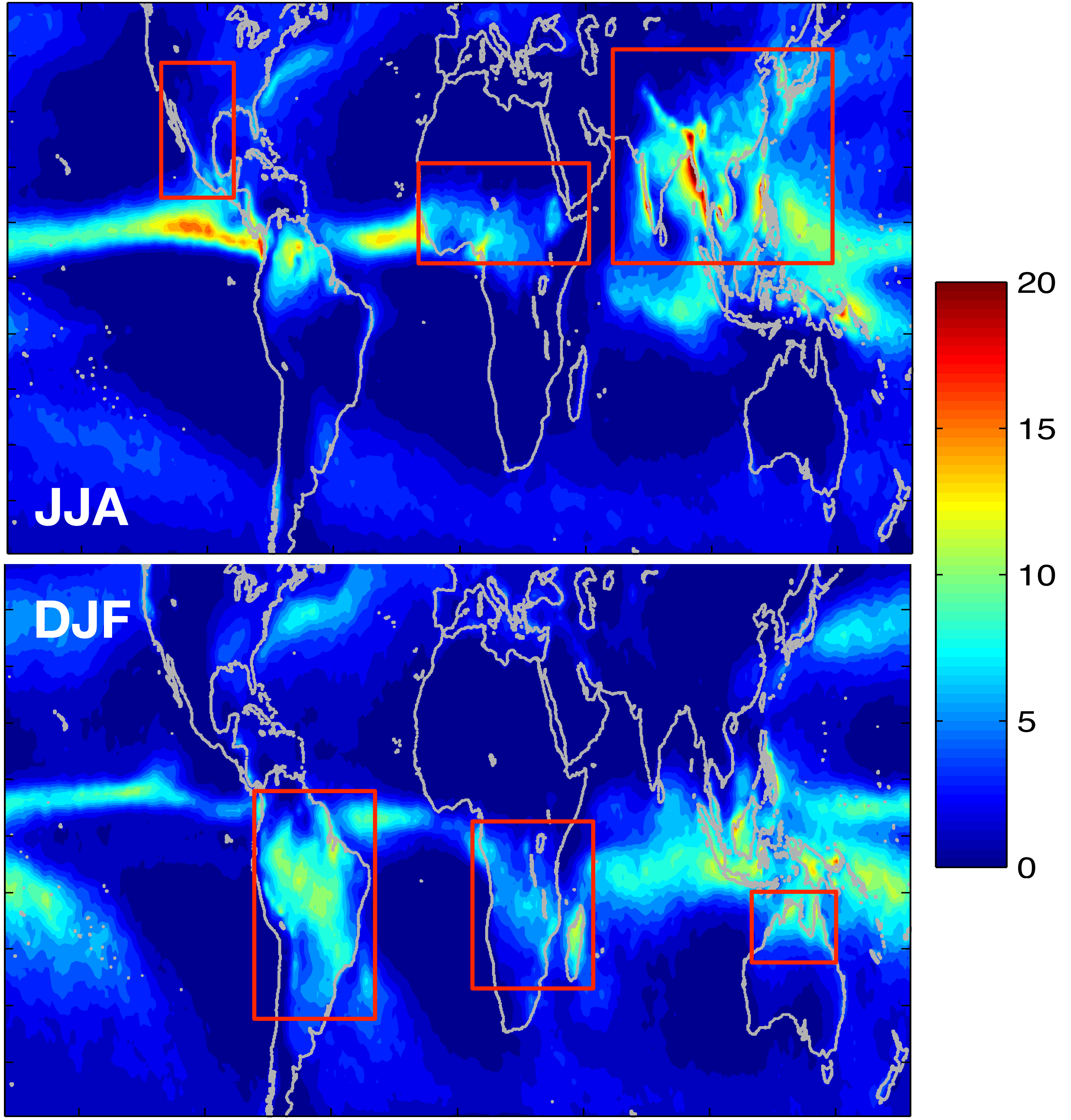
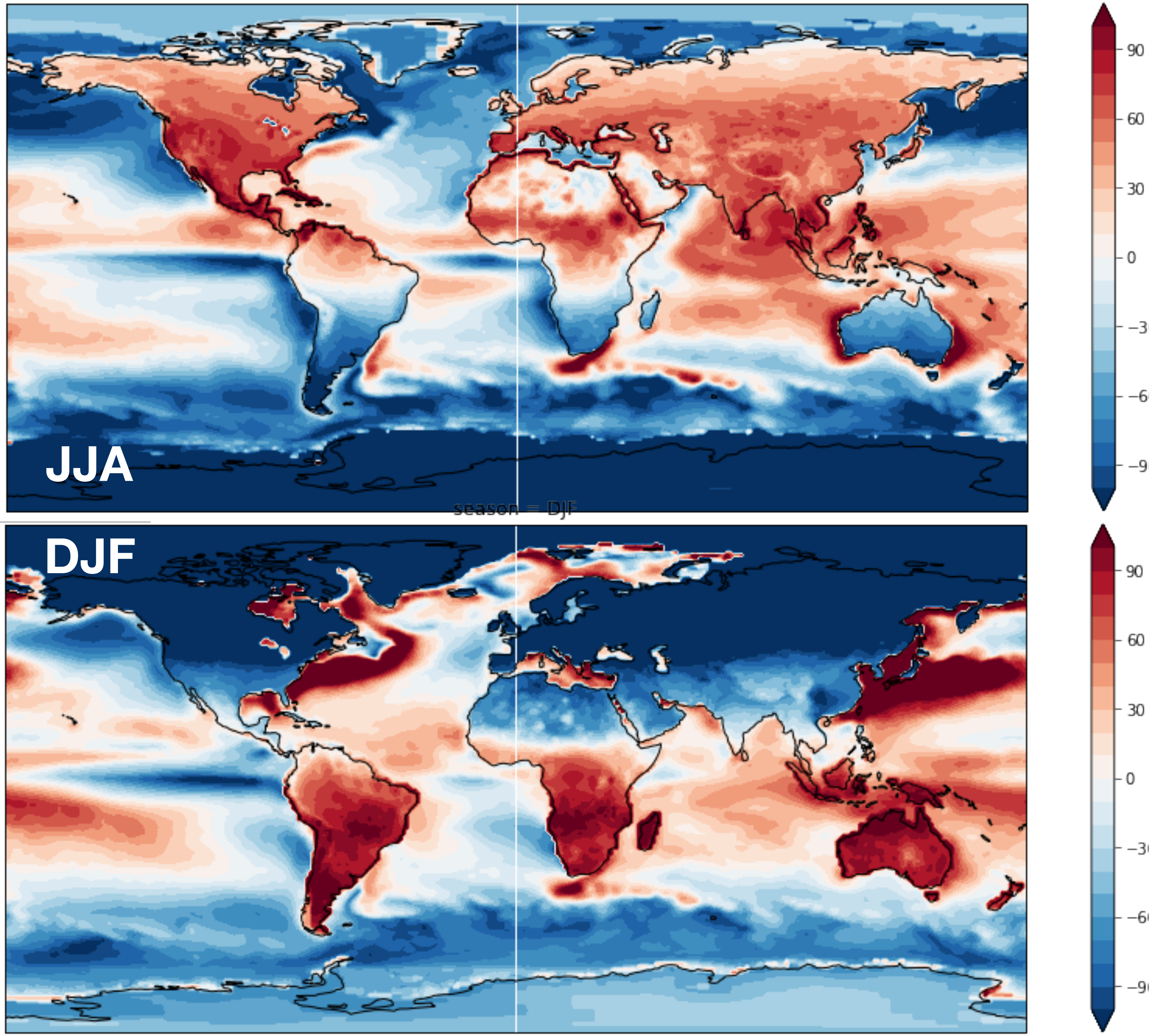


The net energy input to the atmosphere drives this seasonal cycle of rainfall

South Asia is unique, with an oceanic maximum of energy input



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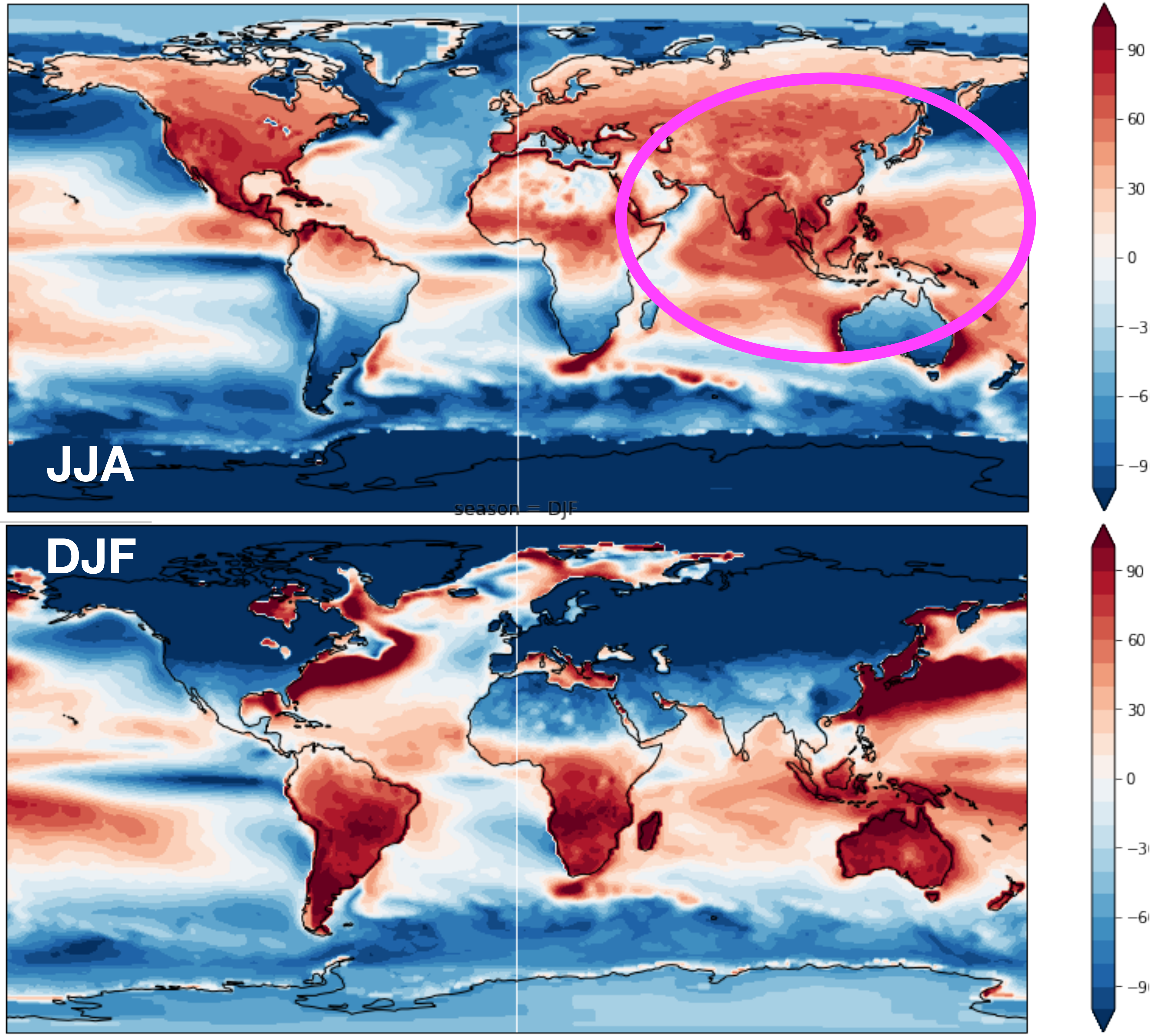

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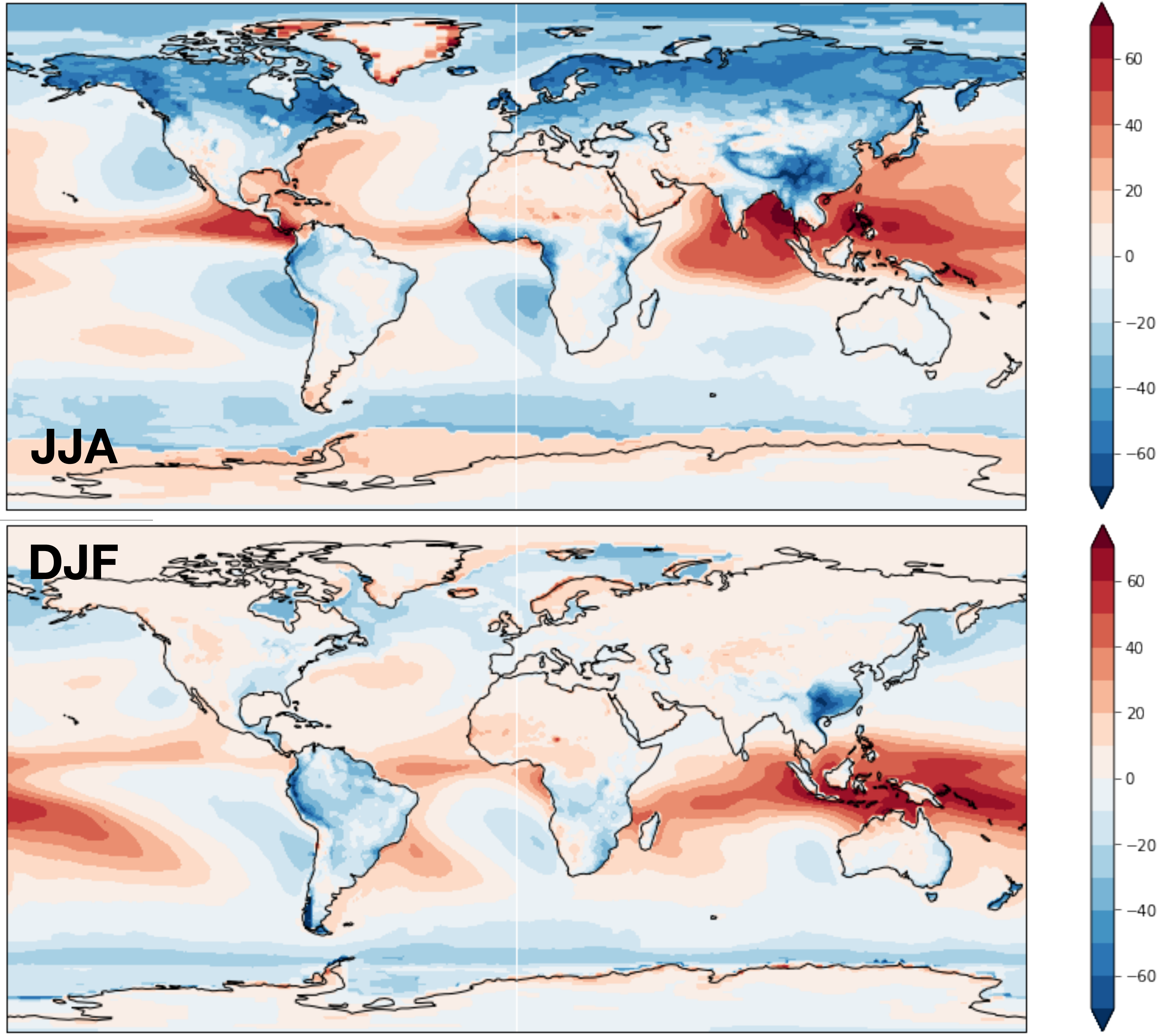
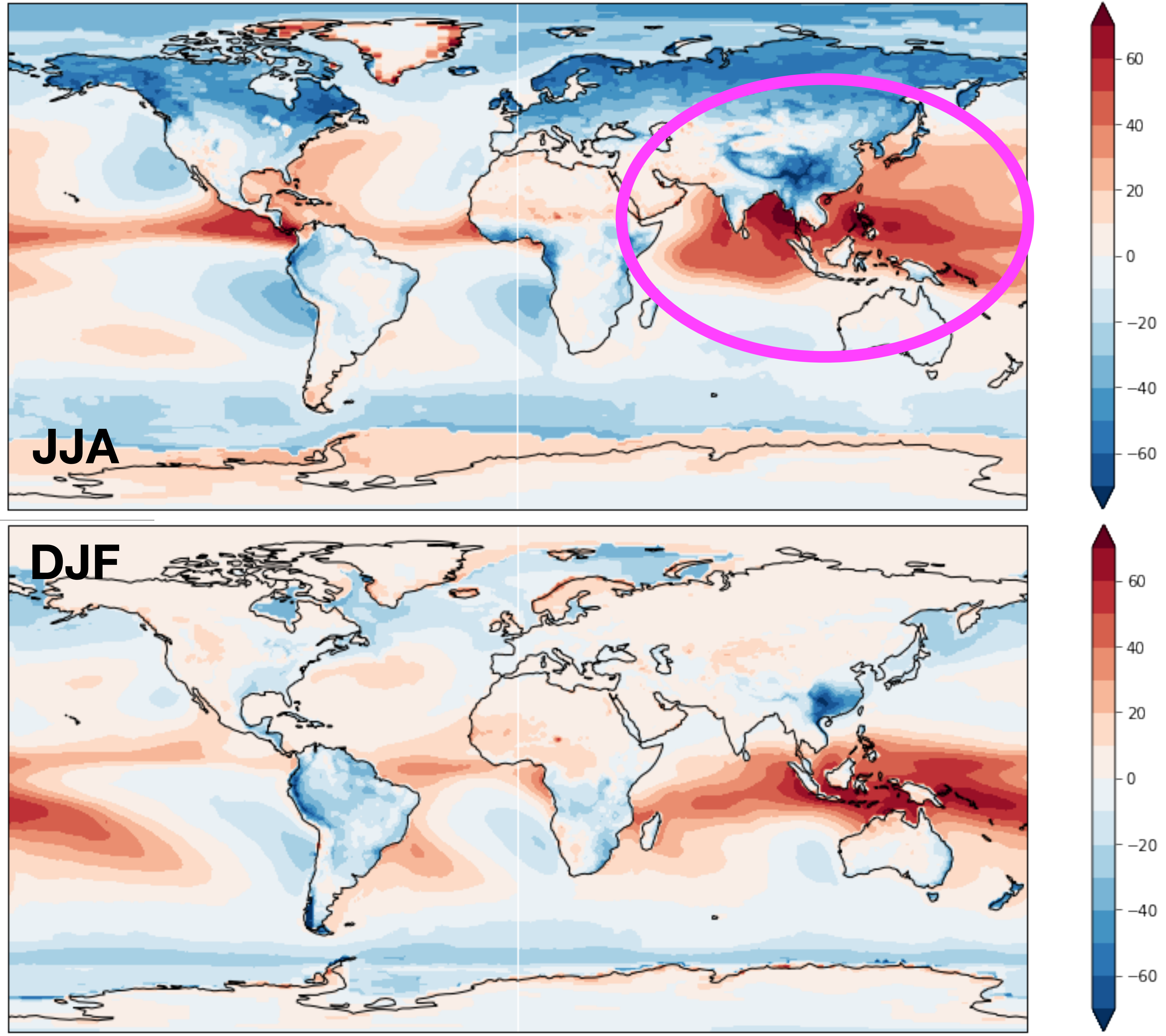
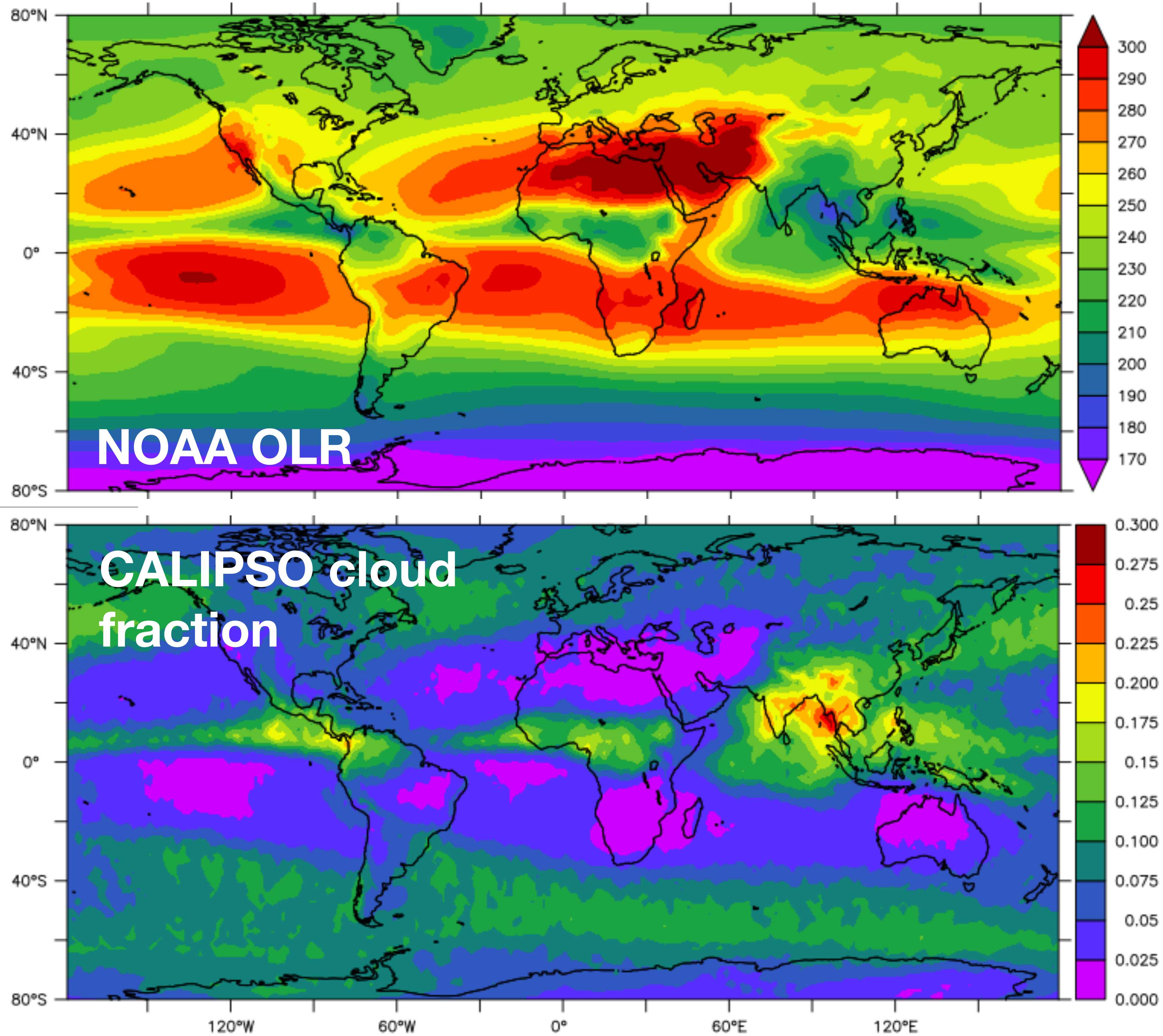
Effect of clouds on net energy input to atmosphere



Effect of clouds on net energy input to atmosphere



Clouds over the North Indian Ocean are colder and more extensive than anywhere else



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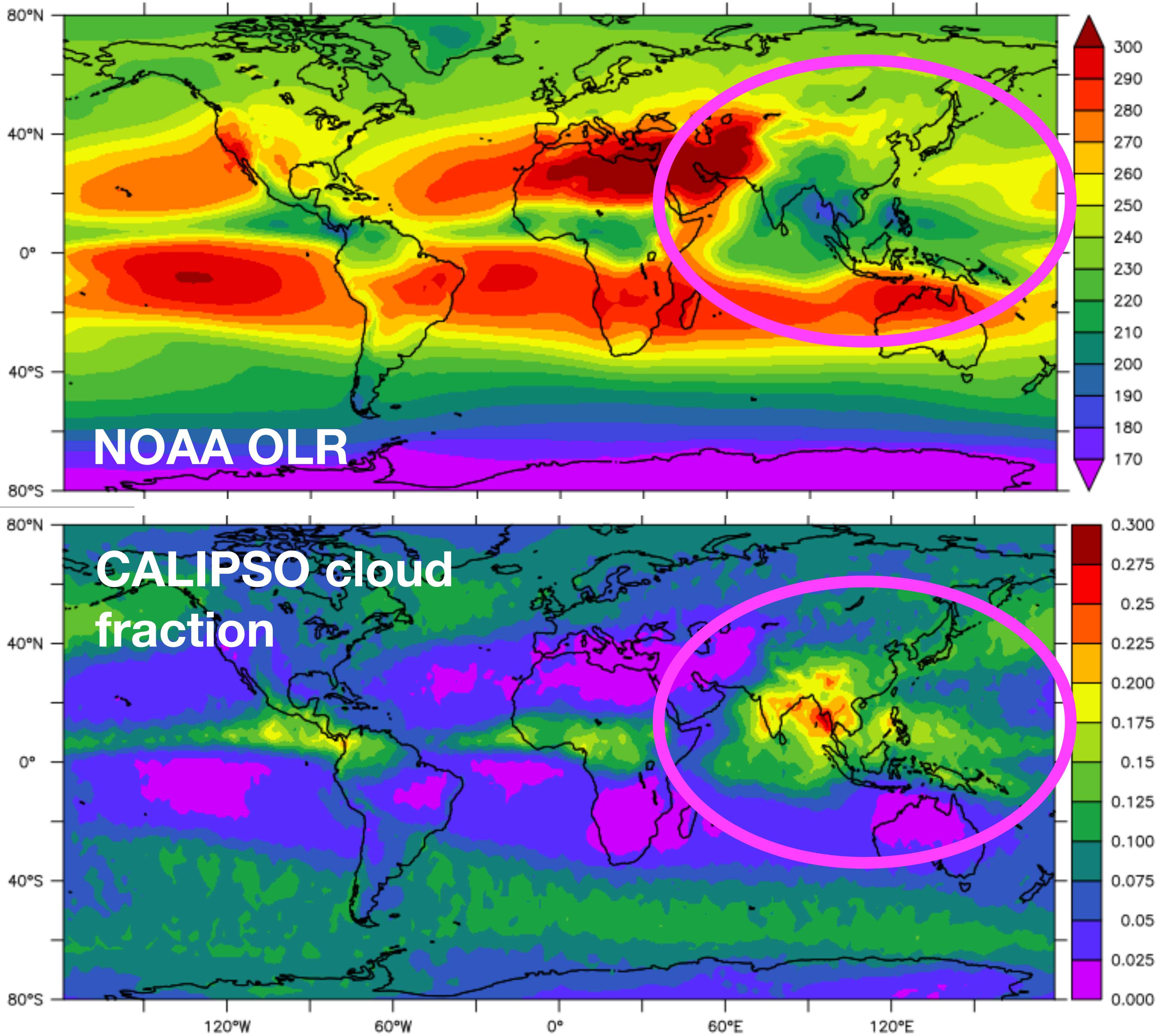
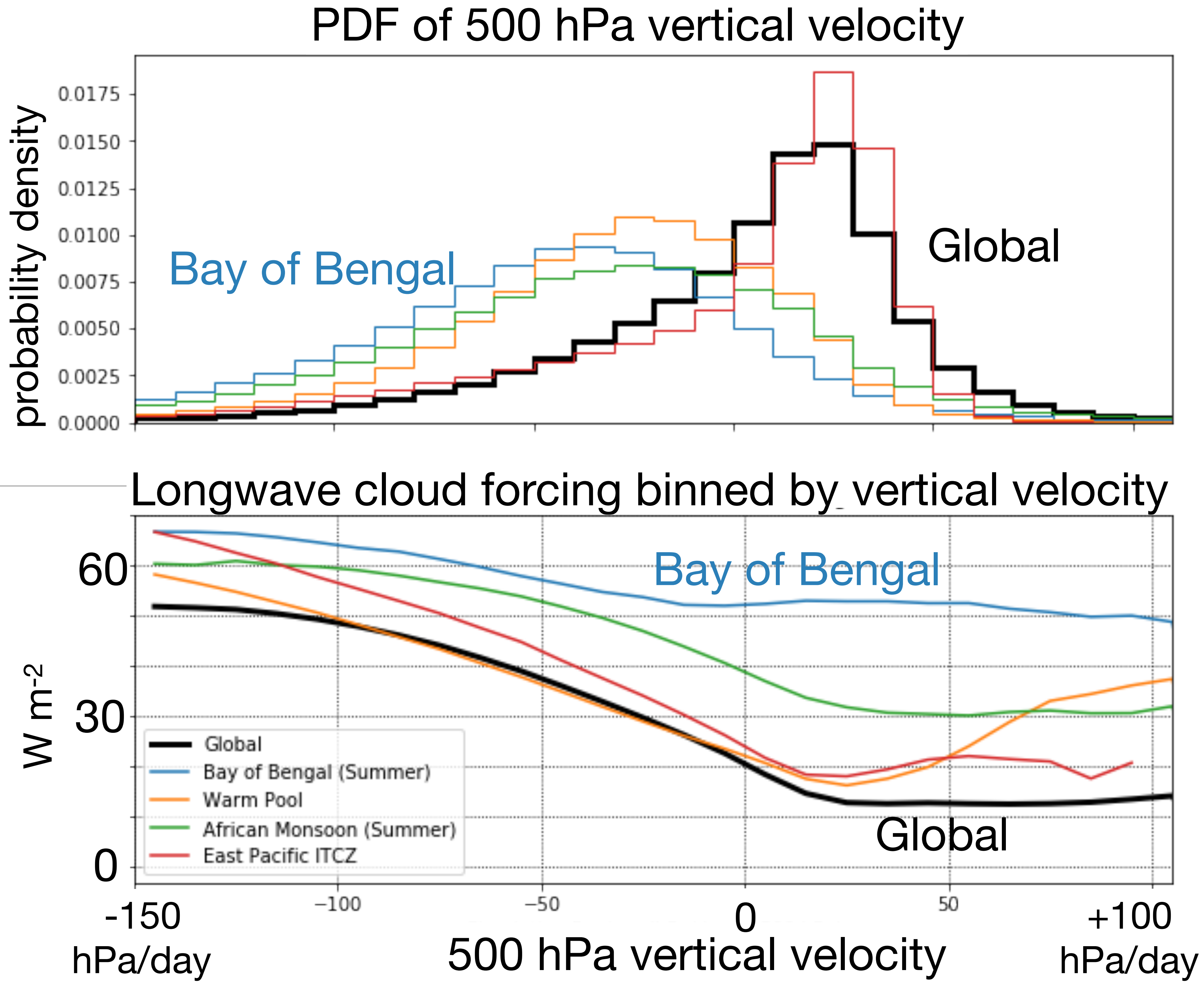


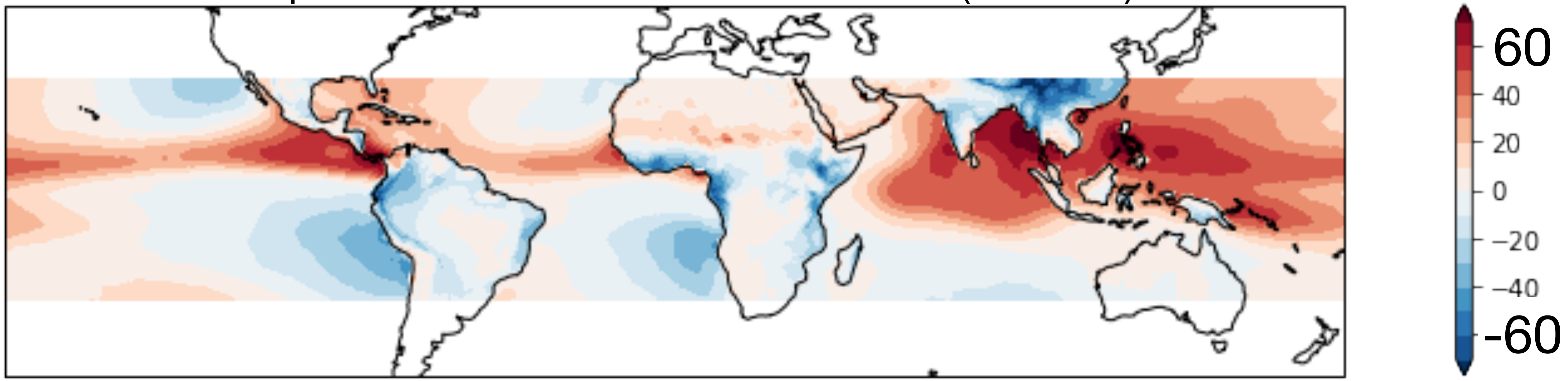
These Indian Ocean clouds have a larger radiative forcing than other regions with similar large-scale ascent

following Bony et al. 2004



Theoretical prediction of the effect of ***tropical*** cloud radiative effect on precipitation

tropical cloud radiative effect (W m^{-2})



$$\nabla^2 \chi' = F'_{\mathrm{net}}$$

$$u'_h \hat{\mathbf{i}} + v'_h \hat{\mathbf{j}} \quad = \quad \nabla \chi'$$

$$P_2(\phi - \delta_\phi, \lambda - \delta_\lambda,) = P_1(\phi, \lambda)$$

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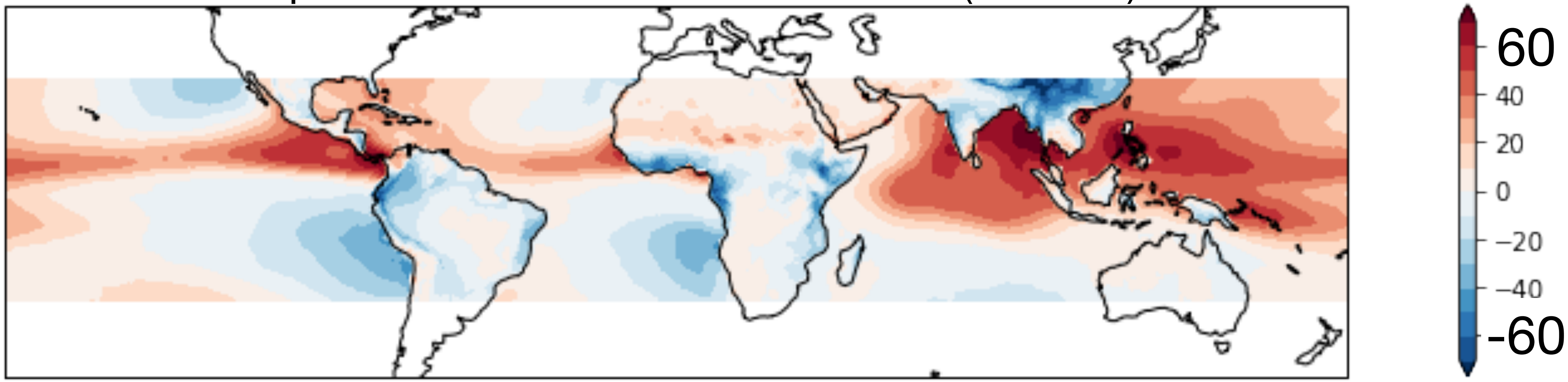
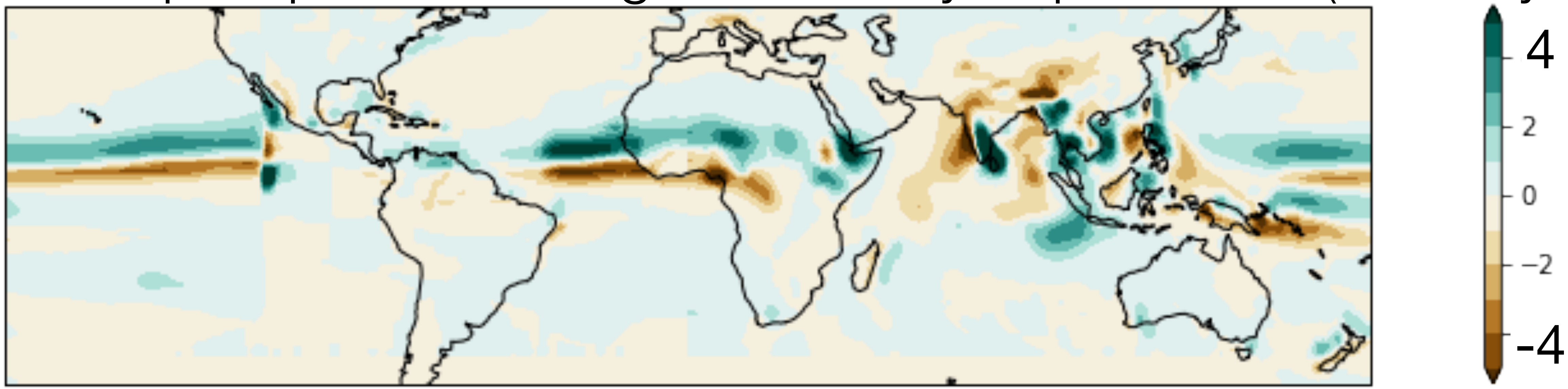


predicted precipitation change caused by tropical CRE (mm day^{-1})



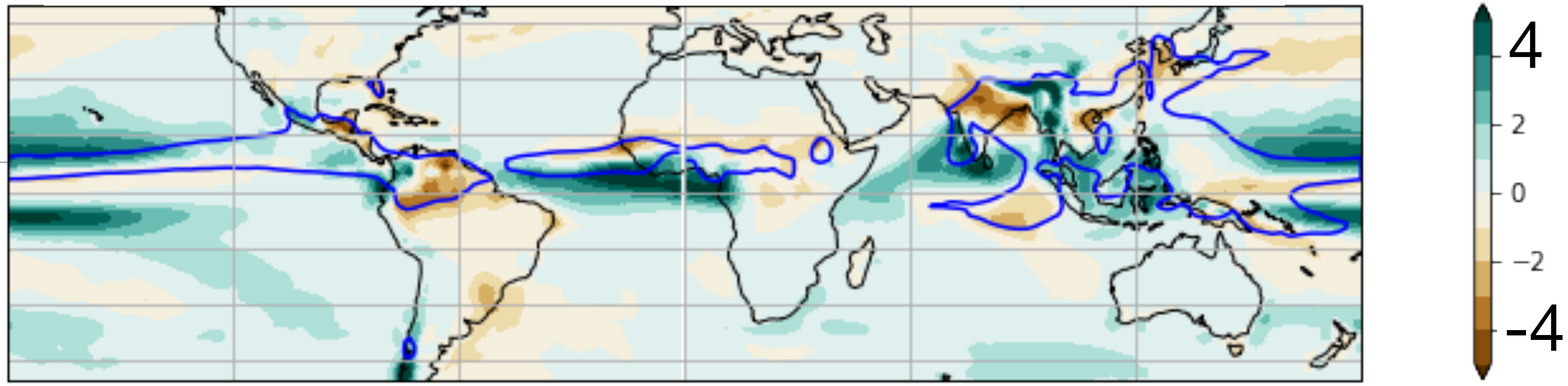
Our two applications

1. Earth's seasonal cycle — some surprising effects of clouds on precipitation

2. **The very persistent precipitation bias in climate models**

CMIP models show a persistent bias in tropical rainfall

CMIP6 precipitation bias (JJA, mm day^{-1})



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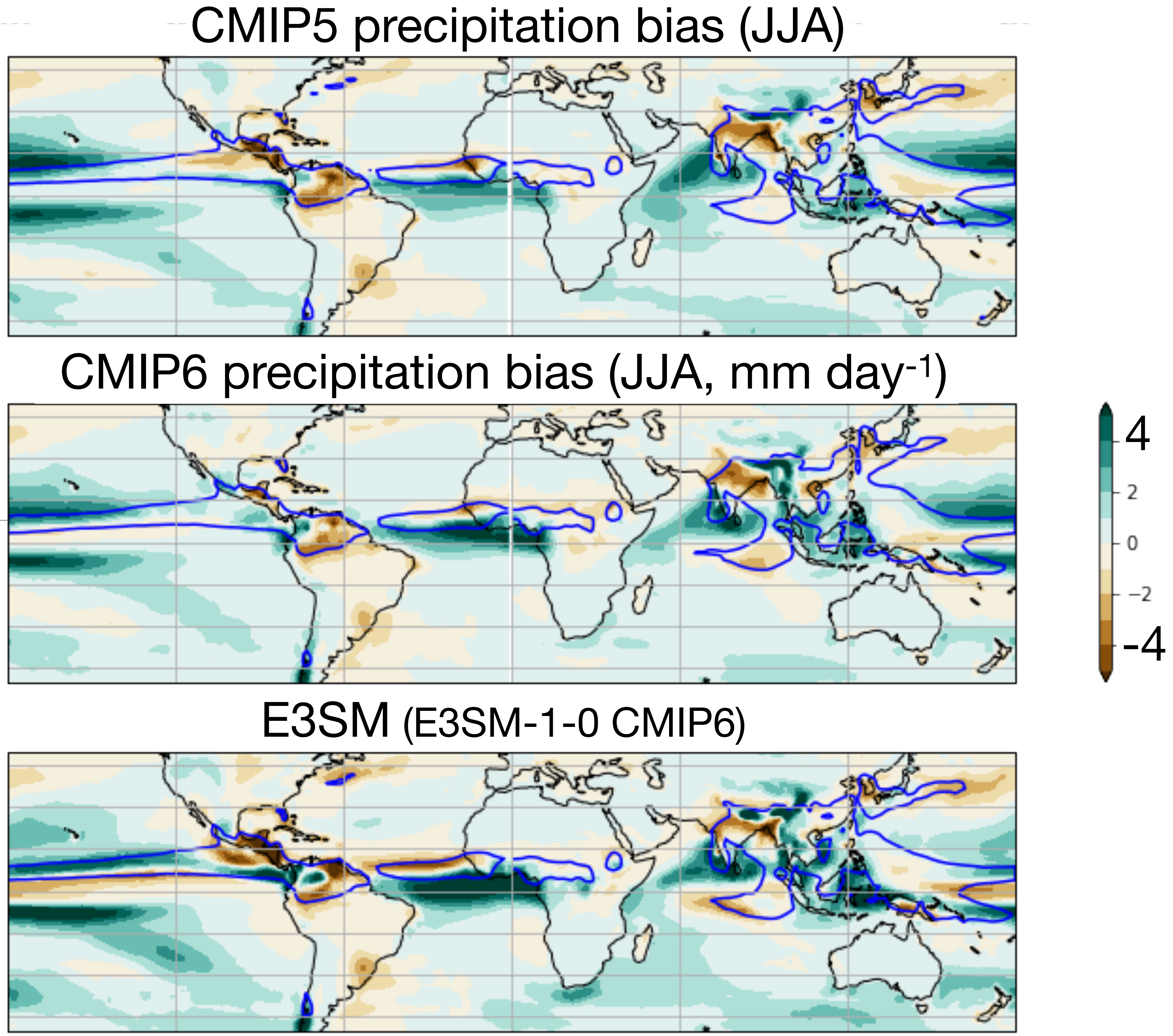
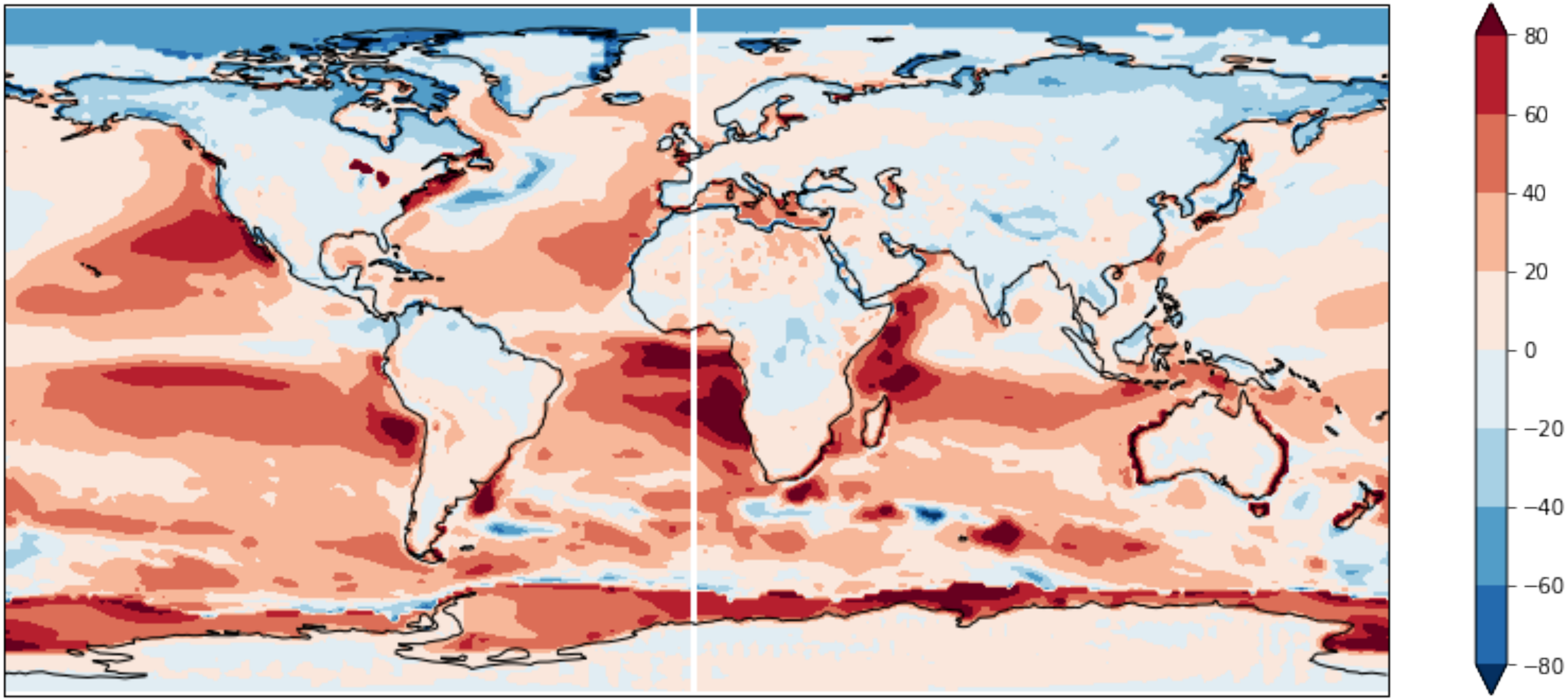


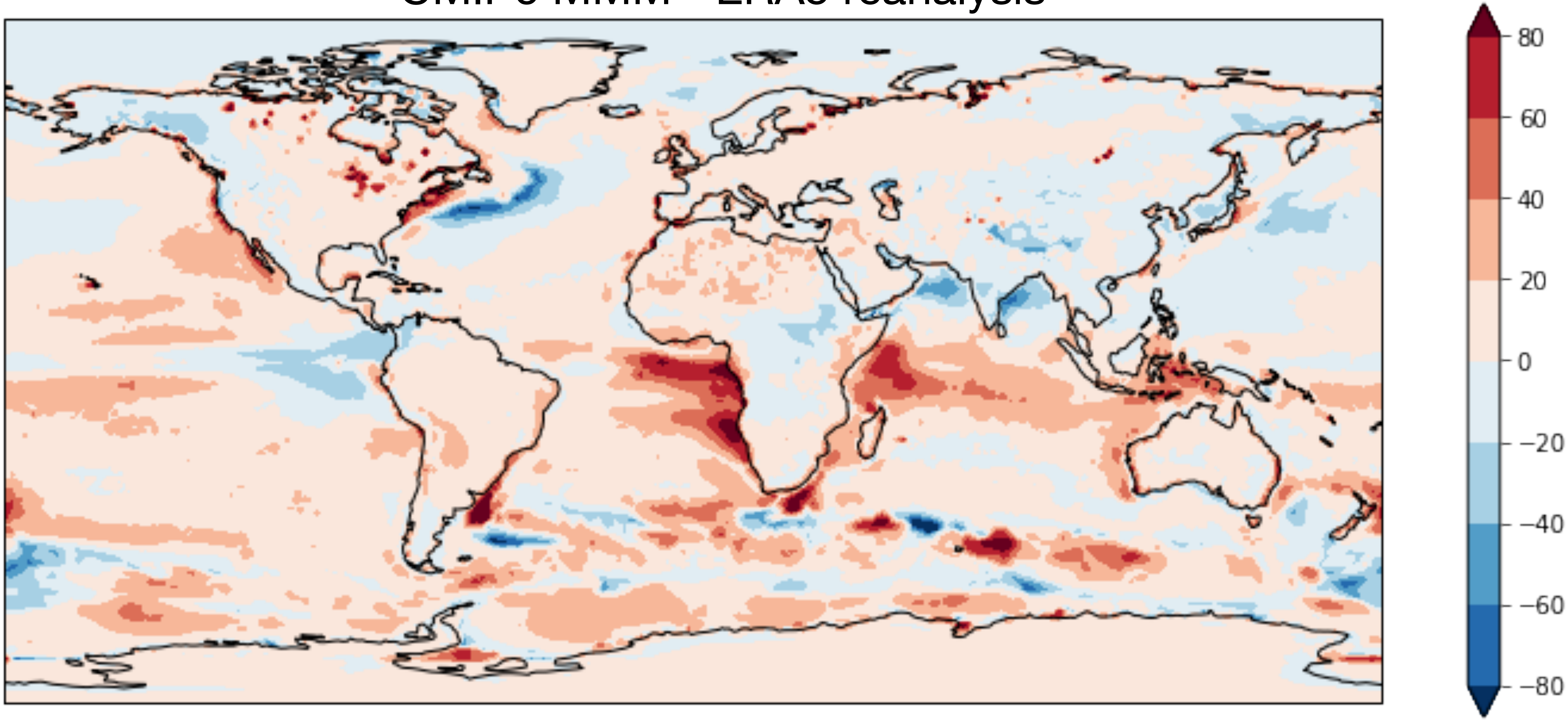
CMIP models also have a large positive bias in net energy input over the Southern Ocean

CMIP6 MMM - observations (CERES+OAFlux)



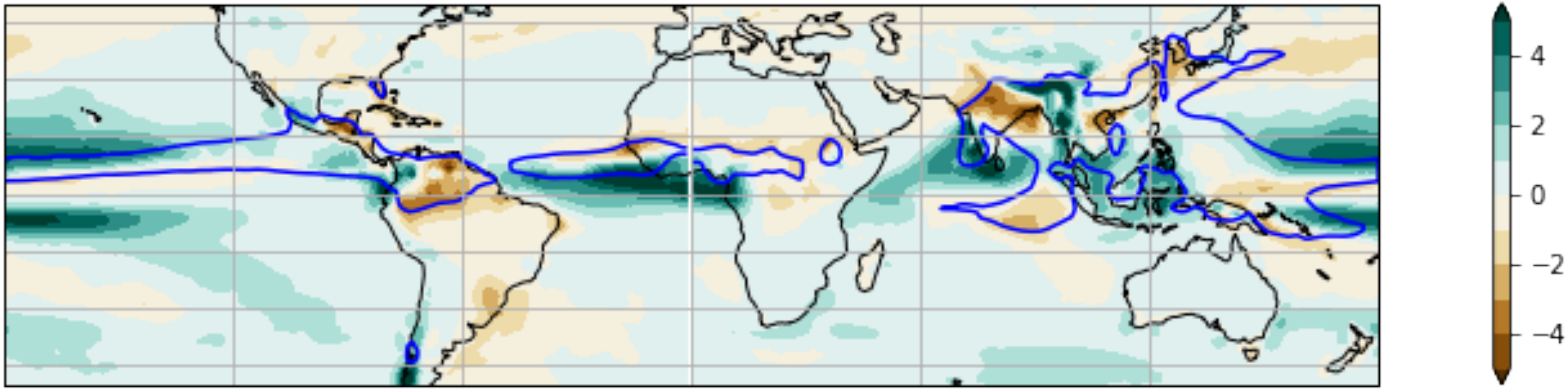
CMIP models also have a large positive bias in net energy input over the Southern Ocean

CMIP6 MMM - ERA5 reanalysis

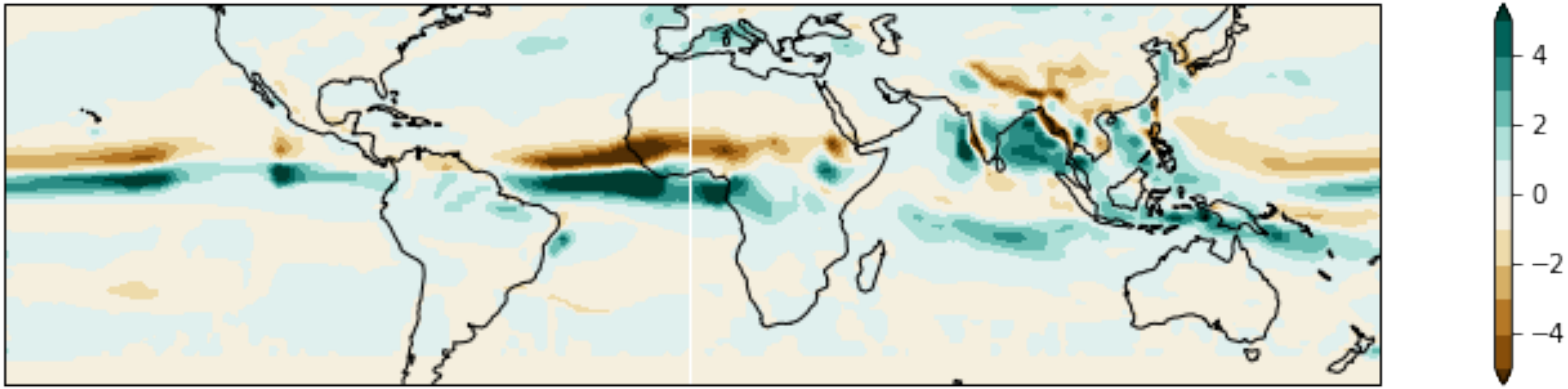


Theoretical prediction of the effect of the CMIP6 MMM energy input bias on precipitation

CMIP6 precipitation bias



theoretical prediction



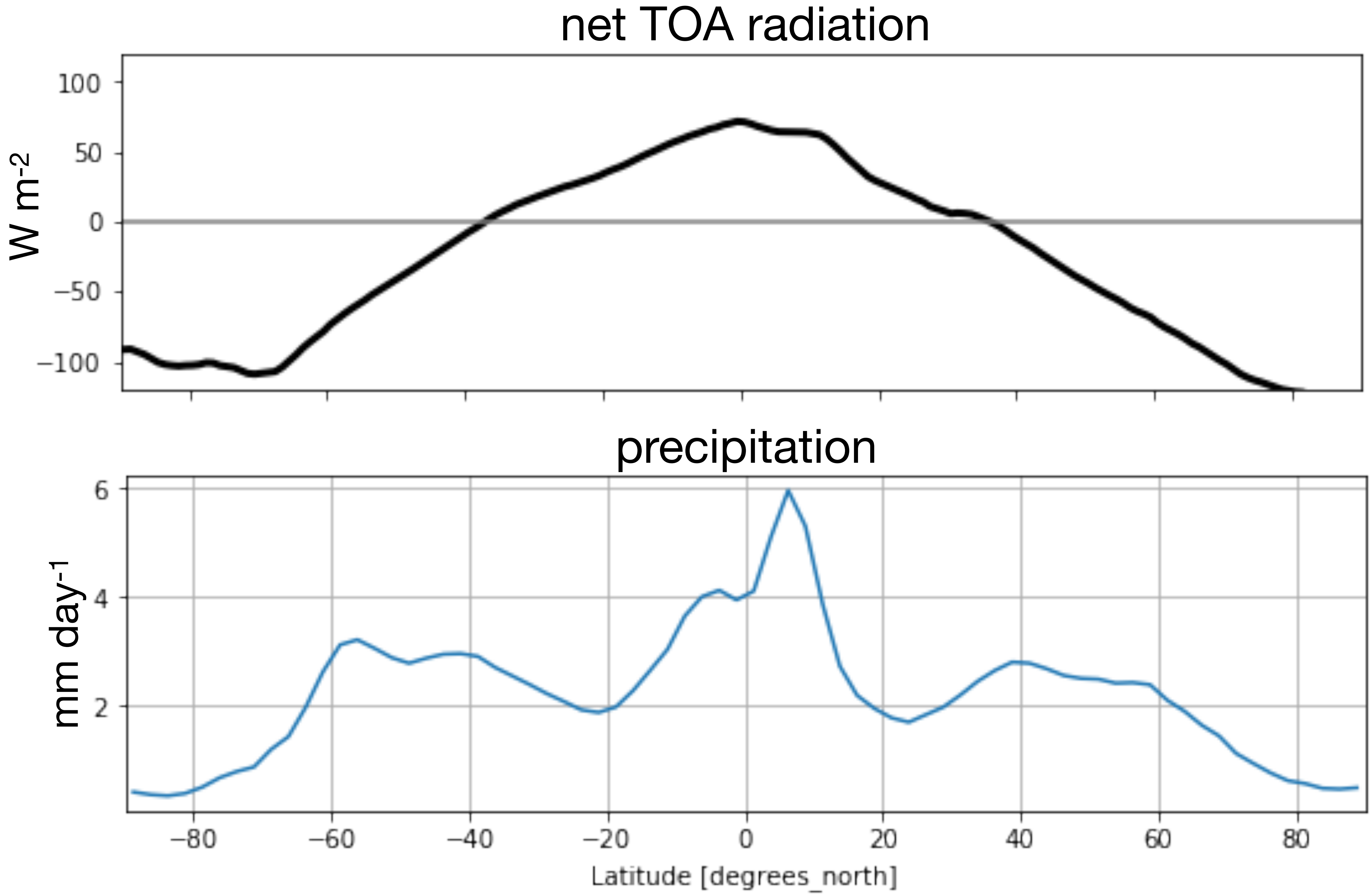
Summary

- Moist energy inputs drive tropical circulations
- 2D (lat-lon) moist energy budget frameworks can help in quantitatively understanding how regional rainfall responds to a variety of forcing
- CERES TOA and surface radiative flux estimates provide an important observational constraint on the net energy input

http://boos.berkeley.edu

Extra slides

The net radiation drives the global atmospheric circulation, which in turn sets the distribution of precipitation



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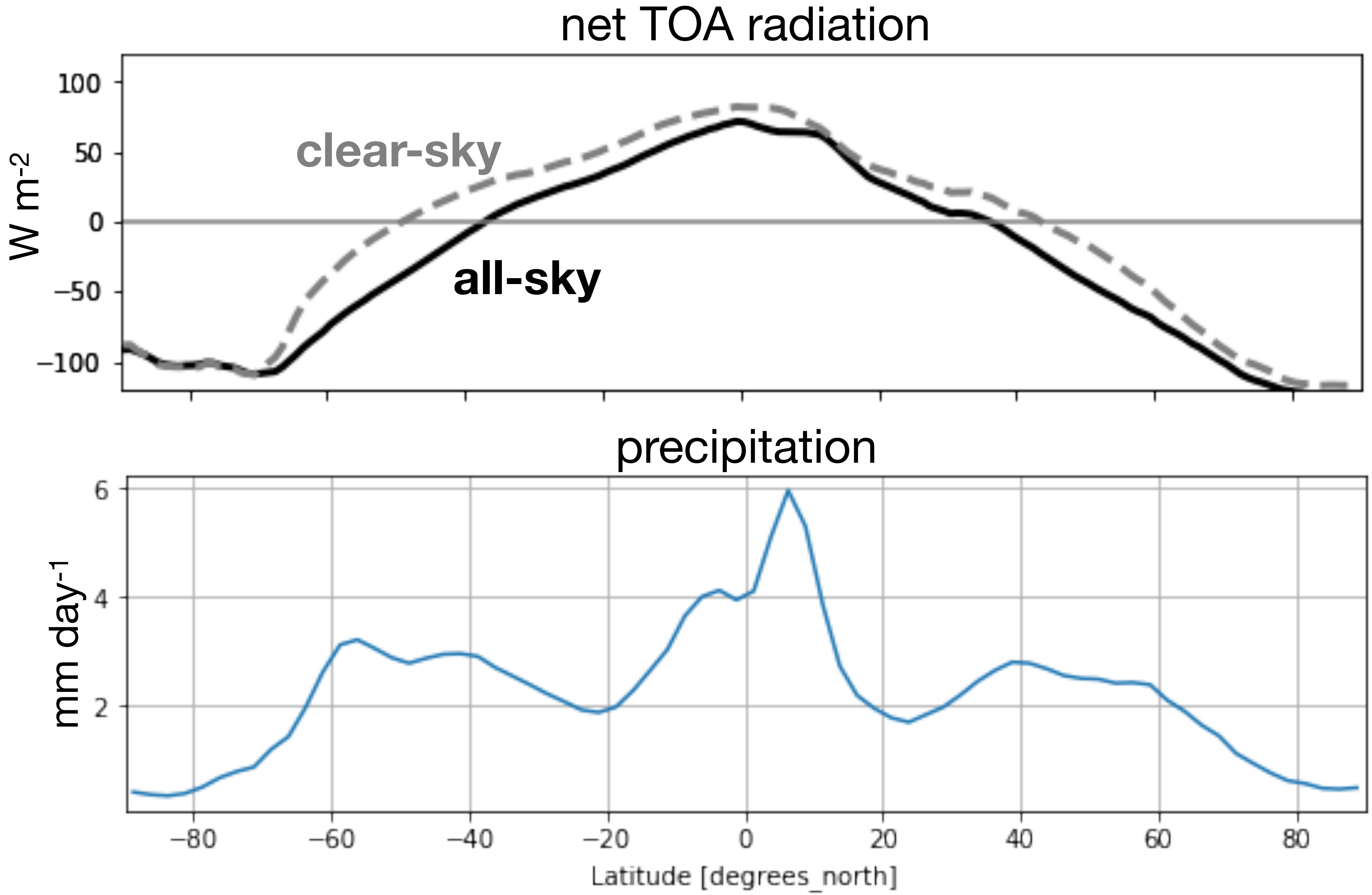
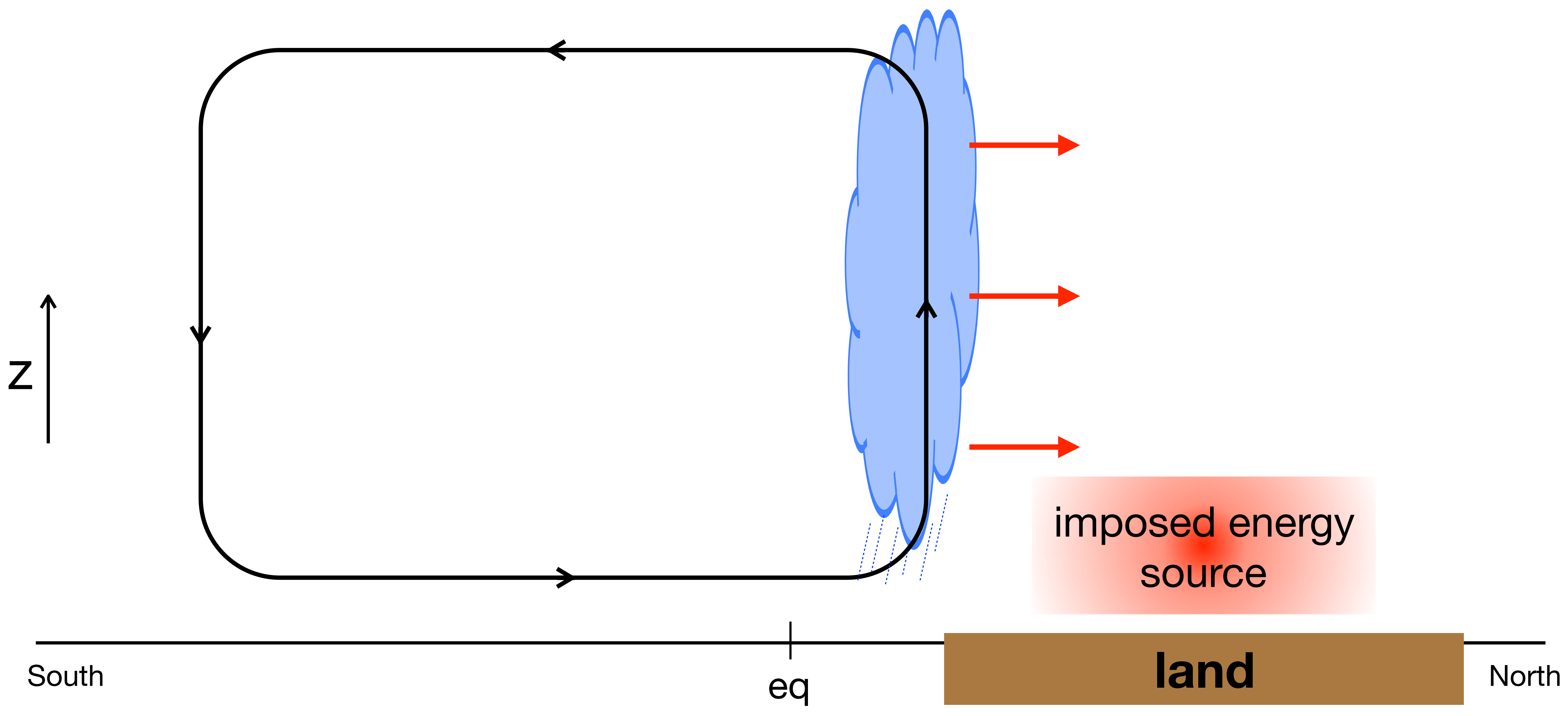
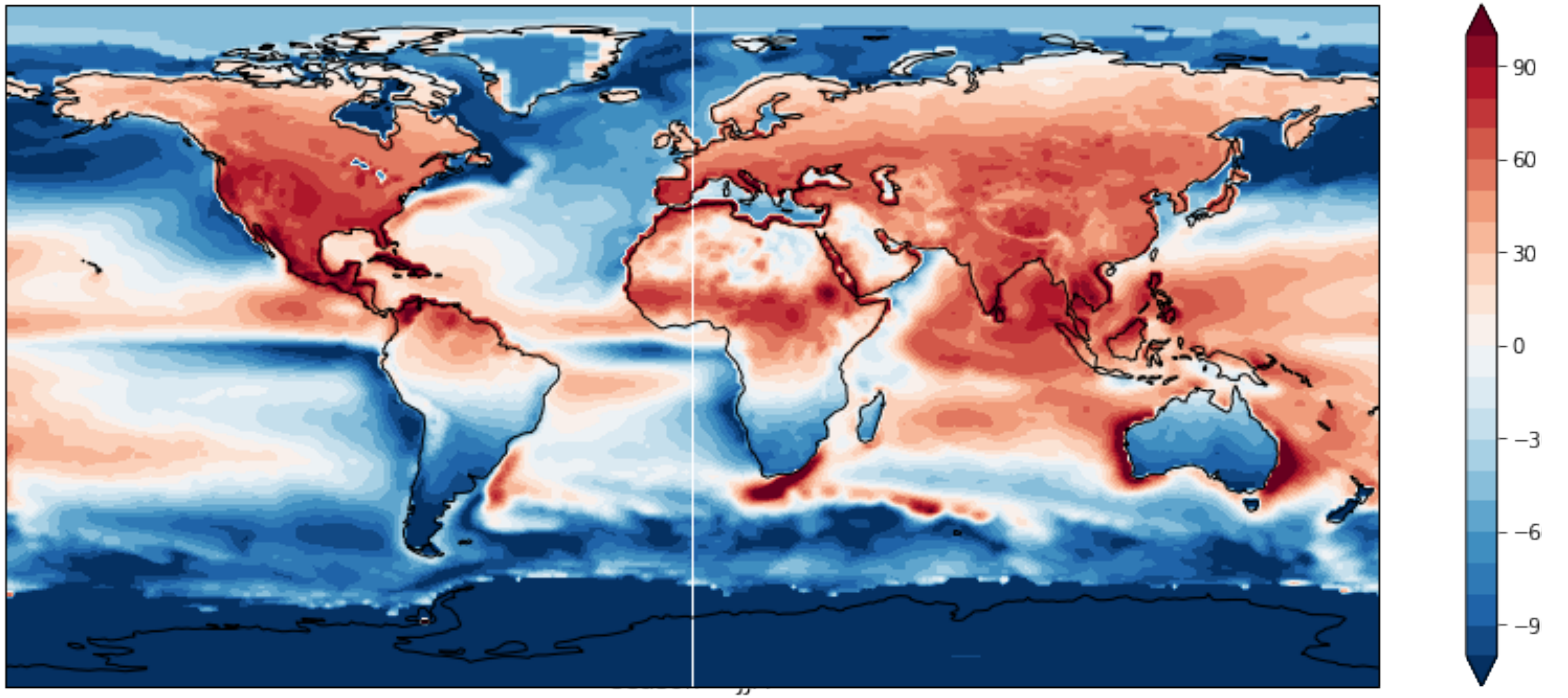
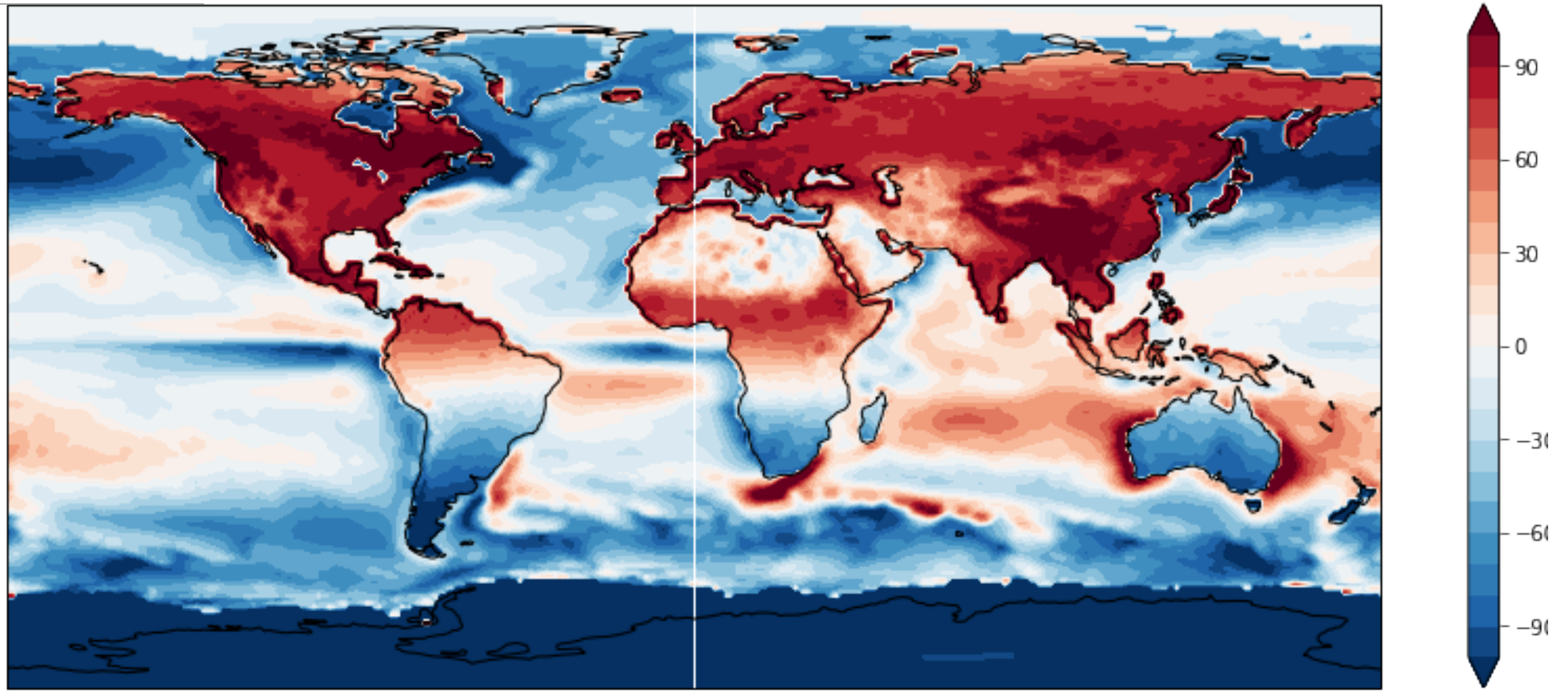


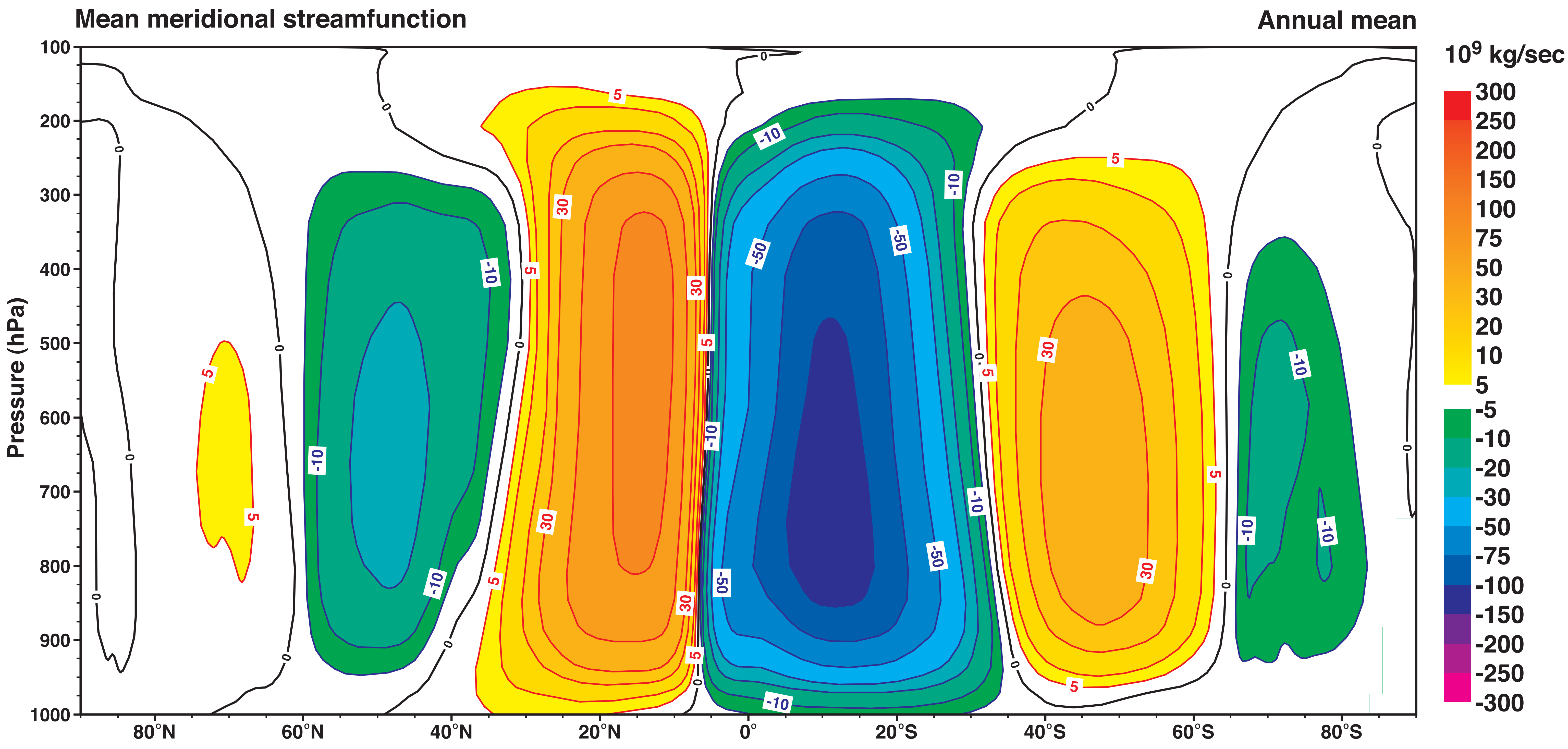
Basic motivating idea:
Tropical rainfall maxima shift toward an anomalous energy source



Effect of clouds

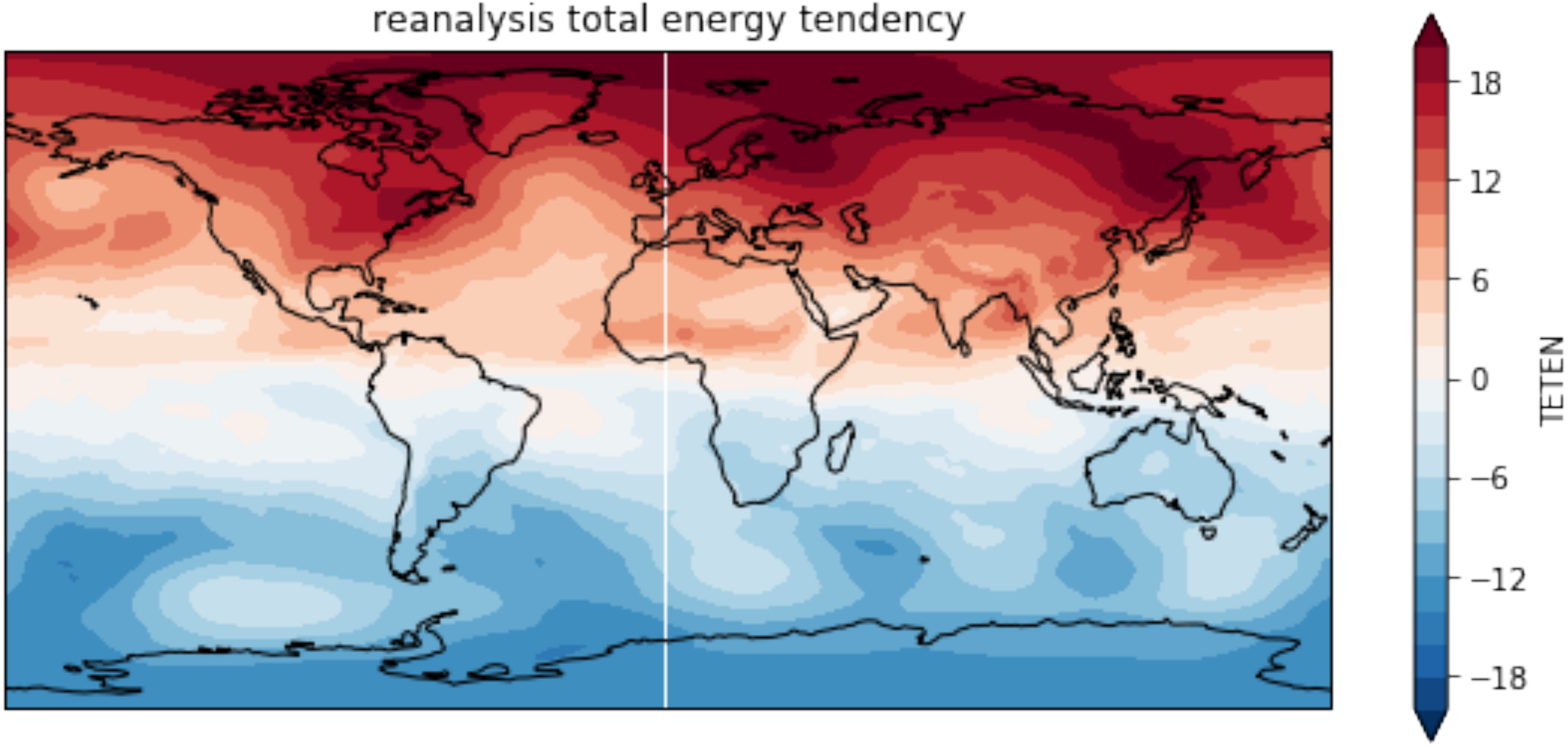




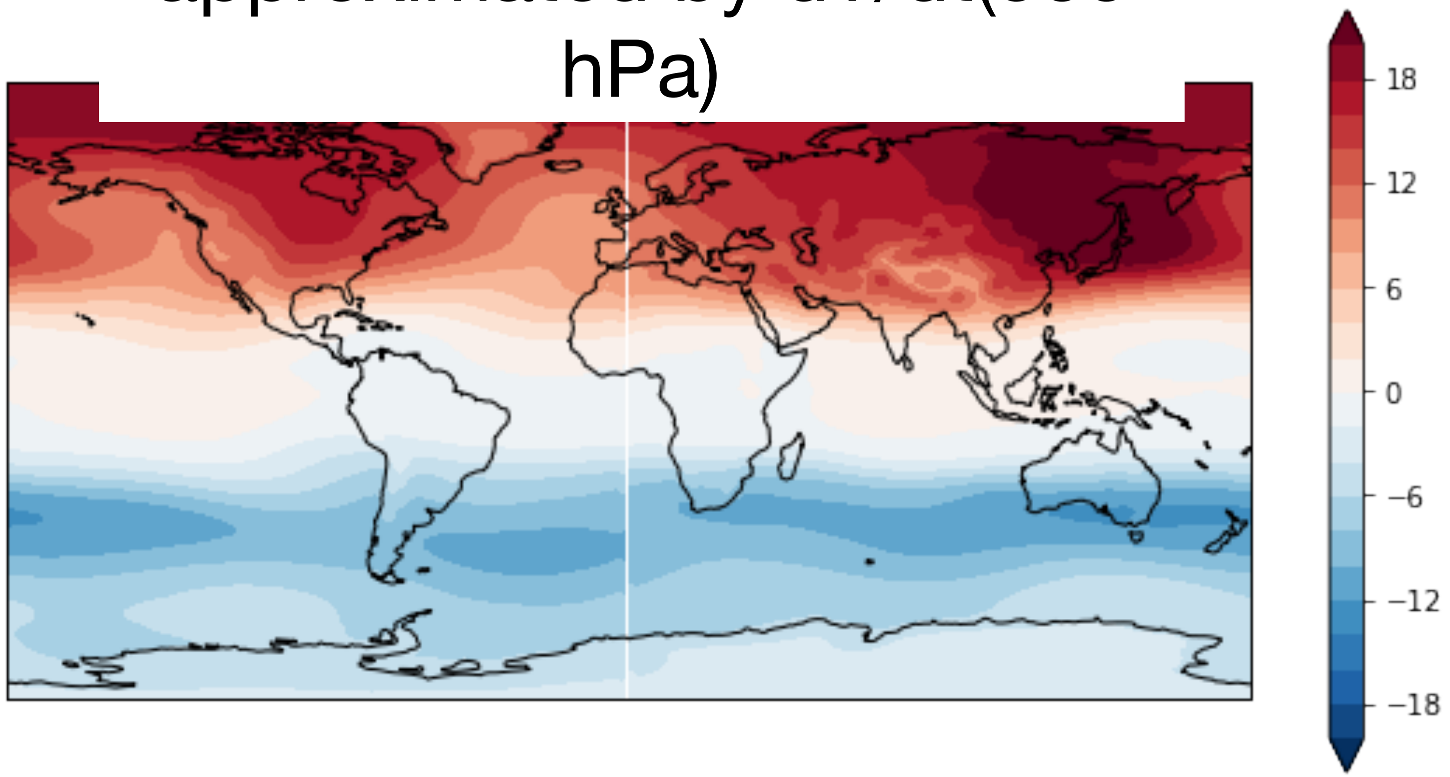


Mean meridional streamfunction
Annual mean
10^9 kg/sec
Pressure (hPa)
100
200
300
400
500
600
700
800
900
1000
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
300
250
200
150
100
75
50
30
20
10
5
-5
-10
-20
-30
-50
-75
-100
-150
-200
-250
-300

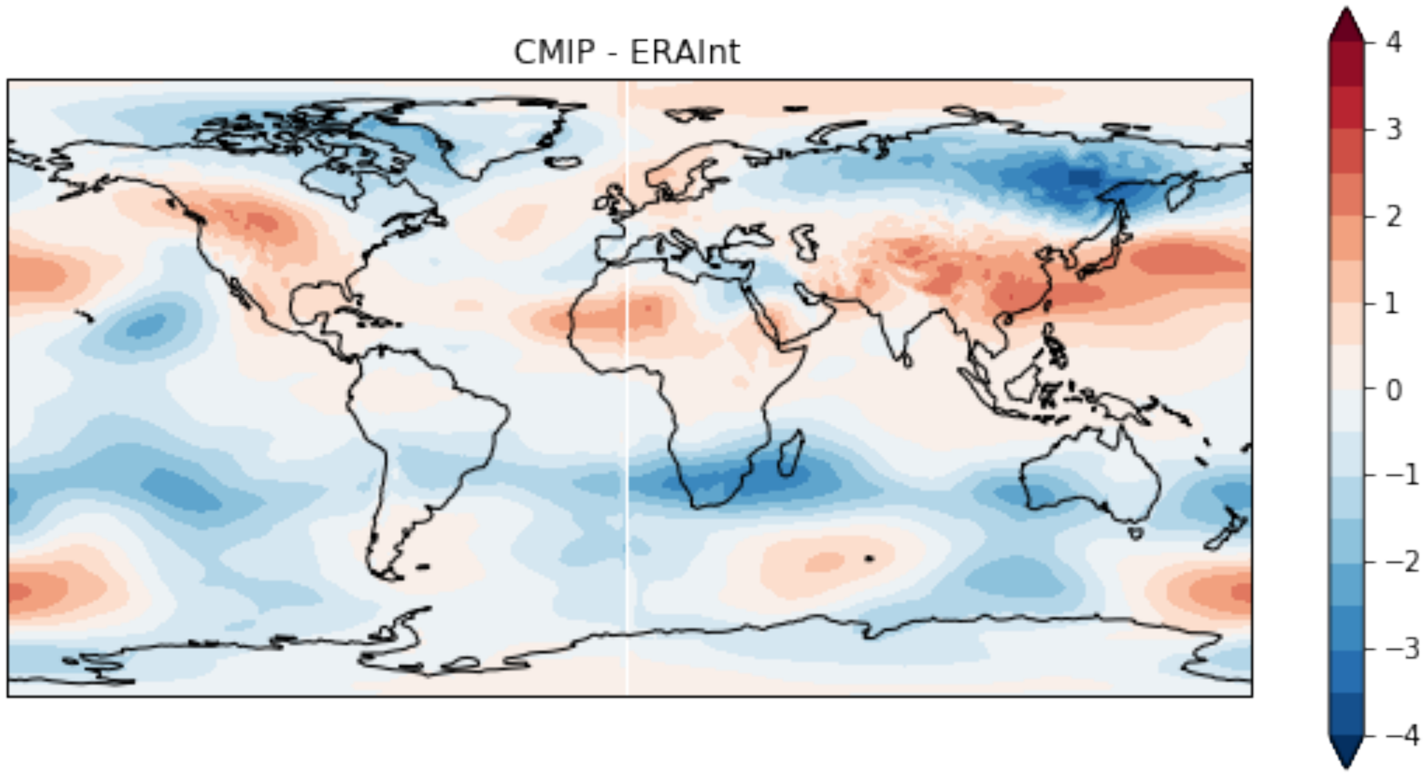
But we've left out the transient energy storage term (here MAM)



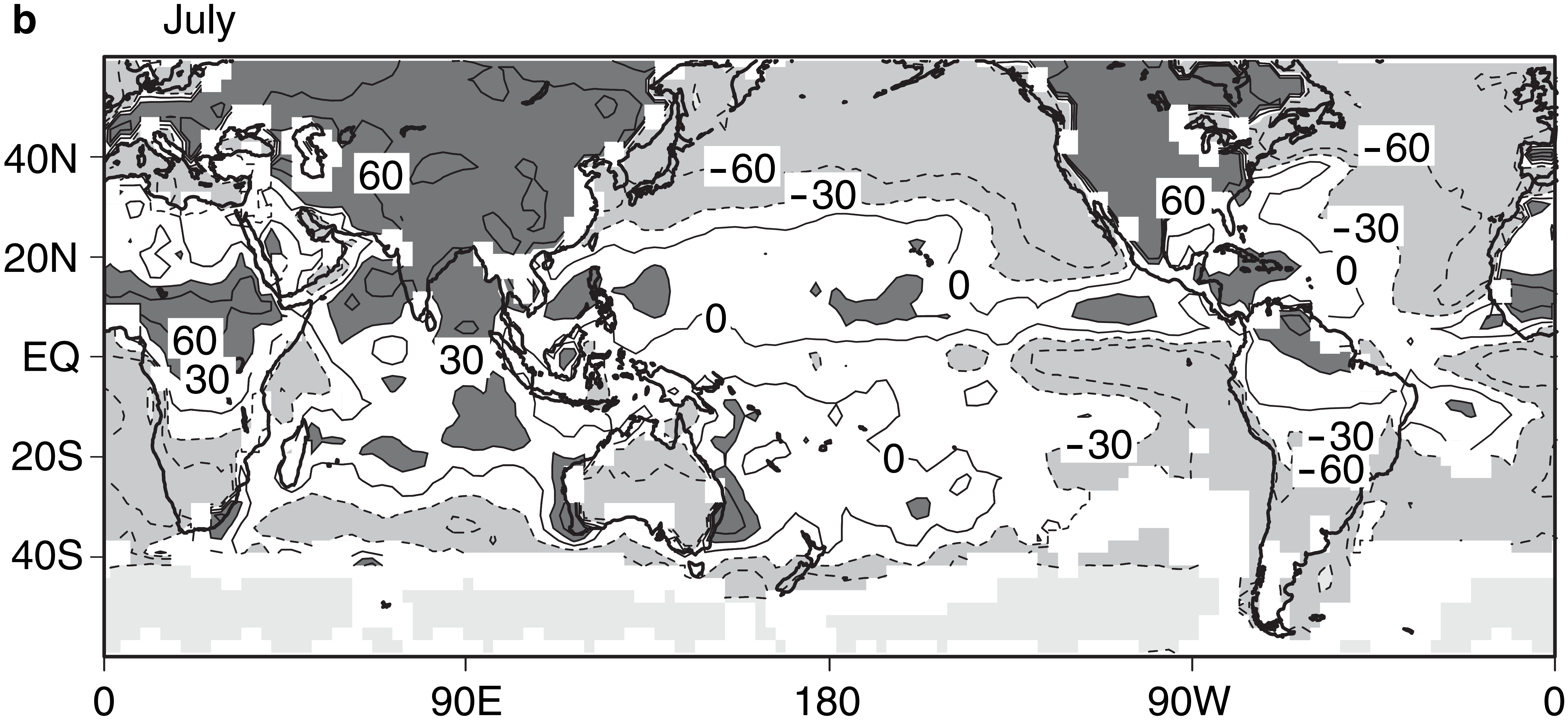
transient storage approximated by dT/dt(500 hPa)



bias



The net energy input to the atmosphere is a central quantity in these frameworks, yet this has received little attention beyond the zonal mean



Neelin (2007), Chou & Neelin (2003), from ERBE and COADS